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Sensor-based detection of the teat load caused by a collapsing liner using a pressure-indicating film

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Kurzfassung

Ziel der Arbeit war es zum Einen die Eignung der Messung statischer Drücke in unterschiedlichen Größenordnungen mit Hilfe von roter Farbdichtevariation zur direkten Messung des Druckes zwischen Zitze und Zitzengummi beim Melken zu testen. Zum Anderen wurden verschiedene Einflussfaktoren auf diesen Druck analysiert. Dafür wurden Untersuchungen im Versuchsmelkstand unter der Verwendung verschiedener Zitzenmodelle durchgeführt. Der Einfluss verschiedener Anlagenvakua, Pulsationsraten, Pulsphasenverhältnisse und Zitzengummis auf die Zitzenbelastung wurde umfangreich analysiert.

Es wurde festgestellt, dass sich die getestete Methode zur direkten Messung des Druckes zwischen Zitze und Zitzengummi eignet. Des Weiteren konnte ein signifikanter Einfluss aller getesteten Faktoren nachgewiesen werden. Die Zitzenbelastung beim Melken nimmt mit ansteigendem Anlagenvakuum, ansteigender Pulsationsrate und ansteigendem Phasenverhältnis zu. Die technischen Eigenschaften eines Zitzengummis, vor allem aber die Form des Zitzengummischaftes, unterscheiden sich signifikant hinsichtlich des von ihnen applizierten Druckes auf die Zitze. In allen Untersuchungen wurde der größte Druck auf das Zitzenende ausgeübt.

Schlagworte: Zitzenbelastung, Druckmessfolie, maschineller Milchentzug

Abstract

The aim of the present thesis was to test whether the measurement of static pressure distribution and magnitude with the aid of red color density variation is appropriate to directly measure the teat load caused by a collapsing liner and to identify different factors influencing this load. Therefore, investigations were carried out in a laboratory milking parlor using different artificial teats. The influence of the machine vacuum, the pulsation rate, the pulsation ratio, and the liner type were analyzed.

The present investigations showed that the tested method is appropriate to directly measure the teat load due to liner collapse. A significant effect of all tested factors could be found as well. The higher the machine vacuum, pulsation rate, and pulsation ratio, the higher the teat load caused by a collapsing liner. The technical characteristics of a liner, especially the shape of the barrel, differ significantly with regard to the teat load. In all investigations more pressure was applied to the teat end.

Keywords: Teat load, pressure-indicating film, machine milking

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List of Abbreviations

ANOVA	Analysis of variance
AP	average pressure
ATB	Leibniz-Institute for Agricultural Engineering and Bioeconomy e.V.
BASE	the teat base measuring area
CA	colored area
CI	confidence interval
COMP	the position where the liner compressed the teat
CORN	the position where the liner did not compress the teat
E1	experiment one
E2	experiment two
END	the teat end measuring area
ER	effective rate
Film 1	Ultra Super Low Prescale pressure-indicating film
Film 2	Extreme Low Prescale pressure-indicating film
L	load
LC	Liner Compression
MA	measured area
MIDDLE	the middle teat measuring area

MP	maximum pressure
OP	over-pressure
PA	pressed area
Q1	25% quantile
Q2	75% quantile
RubCon	a concave rubber liner
RubRou	a round rubber liner
RubRouHV	a round rubber liner with head ventilation
RubSqu	a square rubber liner
RubTri	a triangular rubber liner
Side A	the A-film of the pressure-indicating film
Side C	the C-side of the pressure-indicating film
SilRou	a round silicone liner
STD	standard deviation
TP	Touch Point

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Chapter 1

General Introduction

Introduction

The teat cup liner is the interface between the teat of a dairy cow and the milking technique. A milking system that works improperly can damage the teat and increase the risk of udder infections. The teat-liner interface is affected by biological and physiological (GRAFF, 2006; RUDOVSKY ET AL., 2011) as well as technical factors (HILLERTON ET AL., 2000; ROSE-MEIERHOEFER ET AL., 2009; ROSE-MEIERHÖFER ET AL., 2014). Therefore, the teat cup liner in particular must be very well adapted to the bovine teat. Various scoring systems evaluating teat color, swelling, ring formation at the teat base, and teat end hyperkeratosis are available to evaluate the influence of machine milking on the teat condition (NEIJENHUIS ET AL., 2000; MEIN ET AL., 2001). Sensor-based methods such as ultrasonography (NEIJENHUIS ET AL., 2001a; GLEESON ET AL., 2004), infrared thermography (PAULRUD ET AL., 2005; VEGRICHT ET AL., 2007), and pressure sensors (GATES AND SCOTT, 1986; ADLEY AND BUTLER, 1994; MUTHUKUMARAPPAN ET AL., 1994; DAVIS ET AL., 2001; TOL ET AL., 2010; LEONARDI ET AL., 2015; ROŞCA et al., 2017) are used as well. Nevertheless, there remains a lack of knowledge about the teat-liner interface and the pressure applied to the teat tissue by the teat cup liner during milking because the methods commonly used to detect the effect of the liner type on the bovine teat are very subjective, and the tested sensor-based methods are very complex in terms of their use or have shown limited usability.

Teat anatomy, morphology, and physiology

The bovine udder is composed of four mammary glands. Each mammary gland or udder quarter consists of secretory tissue, an udder cistern to store the milk, and a teat (NICKERSON AND AKERS, 2011). The four quarters of an udder are structurally separate and independent in terms of their function (GRUET ET AL., 2001). The teat is the milk-executing organ of the udder (GRAF, 1982), and it composes the teat wall, the teat cistern, a single narrow teat canal, and the teat orifice (Figure 1) (HIBBITT ET AL., 1992; FERDOWSI ET AL., 2013). It is covered by thick stratified squamous keratinizing epidermis without hair follicles and sweat or sebaceous glands (HIBBITT ET AL., 1992). Three tissue layers form the teat wall: the skin, the middle layer, and the mucosal layer (FASULKOV ET AL., 2014). The teat skin is formed by the epidermis, which contains a keratinized stratified squamous epithelium, and the dermis, which is formed from a network of collagen fibers, blood vessels, circular smooth muscles, and nerve fibers (FERDOWSI ET AL., 2013). The epidermis is banded into the dermis and scatters shear stress from the surface through deeper tissues. Thus, the teat is well adapted to shear stress (HIBBITT ET AL., 1992). The teat skin is tightly attached to the underlying tissue (FERDOWSI ET AL., 2013) and therefore is immobile (HIBBITT ET AL., 1992). Numerous bundles of smooth muscle form the middle layer of the teat wall, contributing to its strength. These muscle bundles are aligned in longitudinal, circular, and oblique planes (HIBBITT ET AL., 1992). The middle layer is the thickest layer of the teat wall (FERDOWSI ET AL., 2013). Depending on the breed and individual cow, the teat wall thickness ranges between 7.1 and 9.0 mm (KLEIN ET AL., 2005). BOBIC´ ET AL. (2014) found teat wall thicknesses between 5.90 and 7.64 mm. The teat wall thickness measured by FASULKOV ET AL. (2014) was, on average, 5.26 mm. The layers of the teat wall have elastic properties (ESPE AND CANNON, 1942). The teat cistern is connected to the udder cistern and has circular and longitudinal folds (GRUET ET AL., 2001). It is lined by a double-layered epithelium and has connective tissue fibers as well as blood vessels in the loose connective tissue below the epithelium (VANGROENWEGHE ET AL., 2006). The teat cistern width ranges between 9.93 and 14.72 mm (BOBIC´ ET AL., 2014). FASULKOV ET AL. (2014) measured a mean teat cistern diameter of 16.07 mm. The teat cistern holds 10-50 ml milk and terminates at the teat canal, which is the opening through which milk is removed (NICKERSON AND AKERS, 2011). The teat canal is a longitudinally folded cylinder-shaped body opening and is covered with almost the same type of epithelia as normal skin (PAULRUD, 2005). PAULRUD AND RASMUSSEN (2004) described the teat canal as an invagination of the outer teat surface. The teat canal forms the inner surface of the teat end and connects the teat cistern to the teat orifice (PAULRUD, 2005). According to AȘTI ET AL. (2011), the teat canal is covered with stratified squamous keratinized epithelium and terminates proximal to the point of the Fürstenberg's rosette (PAULRUD, 2005). The Fürstenberg's rosette consists of six to ten longitudinal folds (NICKERSON AND AKERS, 2011), its region is lined with two layered epithelium, and it plays an important role in the immune defense of the teat because the number of immune cells increases towards the Fürstenberg's rosette region (AȘTI ET AL., 2011). A sphincter of smooth muscle fibers surrounds the teat canal (FRANDSON ET AL., 2009). The teat canal opens as a result of contractions of the muscle fibers. These contractions appear when the teat muscles are stretched due to the presence of milk in the teat cistern (PEETERS ET AL., 1977). It closes via a twisting motion due to a recoil of the elastic fibers within the teat canal structure (GIESECKE ET AL., 1972). The teat canal lumen is normally closed by star-shaped epithelial folds (FRANDSON ET AL., 2009).

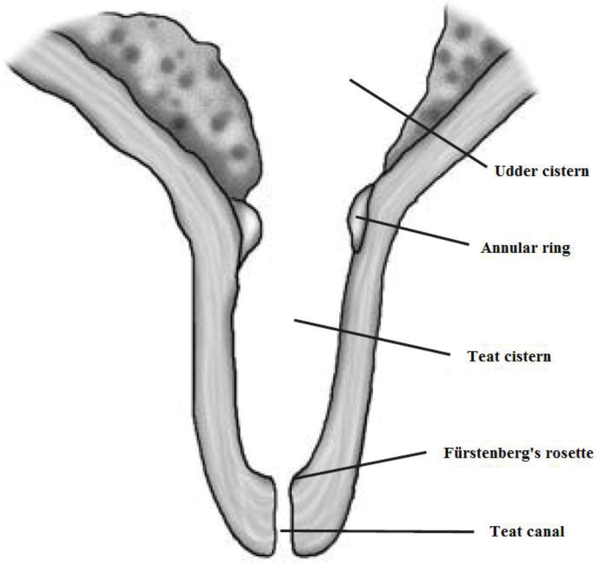

Figure 1. Gross anatomy of the bovine teat (JACKSON AND COCKCROFT, 2002)

Depending on the investigation, the measured teat canal length varied among values of 8 mm (GEISHAUSER AND QUERENGÄSSER, 2000), 15.7-18.6 mm (KLEIN ET AL., 2005), 3-18 mm (PAULRUD, 2005), 11.51 mm (CELIK ET AL., 2008), 8.48 mm (FASULKOV ET AL., 2014), and 12.27-13.38 mm (BOBIC´ ET AL., 2014). Measured teat canal diameters were between 1.7-2.0 mm (KLEIN ET AL., 2005) and 1.92 mm (FASULKOV ET AL., 2014). The principal anatomic structure of the bovine teat is the same for all teats, but it varies in morphologic characteristics according to the breed, individual cow, and individual udder quarter. The teats of German Holstein cows have an average length of 5.0 cm and an average diameter of 2.2 cm. Most teats (99.09%) are cylindrically shaped, and the most common teat end shapes are round, disc-shaped, pointed, and funnel-shaped (HAVERKAMP, 2014). Sarabi Cattle cows have teats ranging in length from 7.0-8.0 cm and a diameter of 3.0 cm. The teats vary in shape from cylindrical to conical (FERDOWSI ET AL., 2013). BOBIC´ ET AL. (2014) found that teats of Simmental cows have an average length and diameter of 5.4 cm and 2.3 cm, respectively. WEISS ET AL. (2004) found an average teat length of 6.2 cm and an average teat diameter of 2.8 cm for crossbred cows (Brown Swiss x German Braunvieh). The front teats of a bovine udder are longer than the rear teats (WEISS ET AL., 2004; ZWERTVAEGHER ET AL., 2012).

ZWERTVAEGHER ET AL. (2012) found slightly smaller tips of rear teats and a larger diameter of front teats.

It can be concluded that the structure of the bovine teat is the same for all teats. However, each teat should be considered individually because of their large morphological variation.

Influence of several factors on teat and teat tissue conditions

Influence of biological and physiological factors

In several studies, the influence of biological and physiological factors on teat conditions was investigated. The risk of the formation of teat end hyperkeratosis depends on the teat morphology. Pointed and convex teats as well as long teats have a higher risk of developing hyperkeratosis (GRAFF, 2006; RUDOVSKY ET AL., 2011). HAEUSSERMANN ET AL. (2009) found that round and pointed teat tips are more likely to develop hyperkeratosis compared with flat or inverted ones. ÖZ ET AL. (2006) used the Finite Element Method to model the effect of teat length on the normal and shear stresses induced on teats during milking, and they did not observe an effect. Genetic influences on hyperkeratosis could be determined as well. GLEESON ET AL. (2003b) found significantly improved hyperkeratosis scores for Montbéliard cattle than for Holstein-Friesian cattle. In almost all cases, front teats have worse hyperkeratosis scores than rear teats (DE VLIEGHER ET AL., 2003; GLEESON ET AL., 2003b; RUDOVSKY ET AL., 2011). In contrast, the amount of teat canal keratin did not differ between rear and front teats (GLEESON ET AL., 2003a). GRAFF (2006) and RUDOVSKY ET AL. (2011) found that an increase in milk flow decreased the formation of hyperkeratosis. Milk flows higher than 3.5 kg/min differ significantly from lower milk flows. A milk flow less than 1.6 kg/min resulted in a strong development of the squamous epithelium in the teat canal (RUDOVSKY ET AL., 2011). The milking frequency did not affect teat end hyperkeratosis (GLEESON ET AL., 2007). The incidence of hyperkeratosis increased with increasing parity (GRAFF, 2006; RUDOVSKY ET AL., 2011) and worsened during lactation (SANDRUCCI ET AL., 2014). CELIK ET AL. (2008) observed an effect of cow age on the teat canal length. The length of the teat canal increases with increasing age. The incidence of hyperkeratosis varied between the seasons of a year (SANDRUCCI ET AL., 2014). There are significant differences between warm, dry (June-September) and wet cold winter months (RUDOVSKY ET AL., 2011).

Influence of milking and milking technique

In general, machine milking influences the condition of a bovine teat. Machine milking results in changes in teat color and teat morphology (MIR ET AL., 2015) and influences the incidence of teat end callosity (NEIJENHUIS ET AL., 2005). STOJNOVIĆ and ALAGIĆ (2012) observed daily changes in the teats of dairy cows caused by milking. Teats of cows milked in an automatic milking system (AMS) show less redness than these of cows milked in a conventional milking system (BERGLUND ET AL., 2002). The authors concluded that milking with an AMS is as good as, and in some cases better than, conventional milking. In contrast, DE VLIEGHER ET AL. (2003) did not find significant differences in teat end conditions between teats of cows milked conventionally and automatically. According to MEIN ET AL. (2003), hyperkeratosis is associated with the type of mechanical milking conditions applied to the teat. HILLERTON ET AL. (2000) compared a 'common' milking cluster (> 200 ml claw volume, 15-16 mm inner diameter long milk tube, 10 mm short pulse tube, < 3.2 kg cluster weight, alternate pulsation) and a 'traditional' milking cluster (150 ml claw volume, 13.5 mm inner diameter long milk tube, 8 mm short pulse tube, 3.5 kg cluster weight, simultaneous pulsation) and observed a better condition of teats milked with the 'common' milking cluster. GLEESON ET AL. (2003a) compared a 'narrow-bore' milking system (1.65 kg cluster weight, 275 ml claw volume, 25.0-20.0 mm narrow-bore tapered liners, alternate pulsation) with a 'wide-bore' milking system (3.2 kg cluster weight, 150 ml claw volume, 31.6-20.6 mm wide-bore tapered liners, simultaneous pulsation) and found significantly lower edema scores for teats milked with the narrow-bore system. In contrast, GLEESON ET AL. (2005) did not find significant differences in teat condition between the two milking systems. The use of a quarter individual milking system with single tubes in milking parlors is usable to avoid turning, tilting, and side forces to the udder (ROSE-MEIERHOEFER ET AL., 2009). Comparison of a conventional milking system and a quarter individual milking system for conventional milking parlors revealed significantly better teat color scores in teats of cows milked with the quarter individual milking system (ROSE-MEIERHÖFER ET AL., 2014). In contrast, ALEJANDRO ET AL. (2014b) found no significant effect of the machine milking on the teat condition of dairy ewes.

The vacuum adjustments of a milking machine influence the teat condition of dairy cows. Excessive machine vacuum use leads to cracks in the epithelium of the teat tissue (WILLIAMS AND MEIN, 1985). HAMANN AND MEIN (1988) investigated the thickness of the teat end in response to different vacuum settings (30 kPa, 50 kPa, and 70 kPa) and found that the teat end thickness rose as the vacuum level increased; the tissue stiffness increased as well (HAMANN, 1988). Comparison between a machine vacuum at 30 kPa, 40 kPa, and 50 kPa showed significant differences in teat thickness (HAMANN ET AL., 1993), and comparison of two different vacuum settings showed that milking at a lower level resulted in fewer color changes of the teat and less cornification of the teat orifice (EBENDORFF AND ZIESACK, 1991). HAMANN and MEIN (1990) compared a machine vacuum of 25 kPa with a vacuum of 50 kPa, and milking with the former reduced the teat thickness by 5%, whereas milking with the latter increased the teat thickness by 10-15%. According to RYŠÁNEK ET AL. (2001), a high vacuum correlated significantly (correlation coefficient of 0.50) with the formation of teat end hyperkeratosis, and reducing the machine vacuum decreased the risk of hyperkeratosis (NEIJENHUIS ET AL., 2005). REINEMANN ET AL. (2001) did not find a significant correlation between the machine vacuum level and the teat end callosity, but they found a tendency towards more teats with worse scores and fewer teats with improving conditions with a vacuum of 50 kPa compared with 42 kPa. In contrast, GLEESON ET AL. (2003b) did not observe an effect of a higher teat end vacuum and vacuum fluctuation on teat end hyperkeratosis. AMBORD AND BRUCKMAIER (2010) did not detect changes in teat condition caused by vacuum changes during milking. PARILOVA ET AL. (2011) tested the influence of two different vacuum levels (39 kPa and 45 kPa) on traits of teat length, teat diameter at the base, teat diameter in the middle, teat canal length, teat end width, teat wall thickness, and teat cistern width. With a higher machine vacuum, the authors found a longer teat and teat canal, a narrower teat diameter at the base and at the middle, a wider teat and teat cistern, and a thicker teat wall. A machine vacuum level of 50 kPa resulted in increased teat wall thickness and a decrease in teat cistern diameter compared with a machine vacuum of 42 kPa (BESIER AND BRUCKMAIER, 2016). The combination of the milking vacuum level and b-phase duration had an effect on the teat wall thickness after milking. The teat wall thickness increased approximately 25% and 35% at milking vacuum levels of 44 kPa and 50 kPa and b-phase durations of 322 ms and 500 ms, respectively (SPANU ET AL., 2008). SAGKOB ET AL. (2010) determined a significant improvement in ring formation at the teat base and hyperkeratosis in teats milked with a milking cluster with periodic vacuum reduction under the teat compared with a conventional milking cluster. VETTER ET AL. (2014) confirmed these results because they found a reduced load on the teat tissue, the development of edema, and an increase in teat wall thickness during milking using the same milking cluster. ROSE-MEIERHÖFER ET AL. (2014) found that a milking system with a low machine vacuum of 37 kPa led to better teat color scores compared with a conventional milking system with a machine vacuum of 40 kPa. RASMUSSEN AND MADSEN (2000) did not find an effect of milking at 38 kPa on teat condition as well. In contrast, a low machine vacuum level extended the milking duration and worsened the teat end condition (REID AND JOHNSON, 2003). Therefore, a machine vacuum or a claw vacuum of less than 30 kPa is not advisable (HAMANN ET AL., 1993; BESIER AND BRUCKMAIER, 2016). Overmilking, which according to RASMUSSEN (2004) starts when milk flow to the teat cistern is less than the flow out of the teat canal, also affected teat condition (HILLERTON ET AL., 2002). EDWARDS ET AL. (2013) determined an increase in teat end hyperkeratosis scores caused by overmilking of more than 2 min. The comparison between overmilked and non-overmilked teats showed that overmilked teats were longer and narrower after milking. Overmilking caused frequent hyperkeratosis and should be limited to a minimum (HAEUSSERMANN ET AL., 2009).

Adjustments of the pulsation of a milking system affect teat condition and teat tissue condition as well. GRINDAL (1988) found that extending the suction phase led to an increase in teat lesions and subcutaneous bleedings. Milking without pulsation resulted in greater teat canal diameters than milking with pulsation (CAPUCO ET AL., 1994) and pulsationless milking led to reduced keratin removal and keratin regeneration rates (LACY-HULBERT ET AL., 1996). HANSEN ET AL. (2006) investigated the influence of different pulsation rates and pulsation ratios on teat thickness and found significant differences between ‘fast’ (dynamic and milk flow controlled pulsation mode, 22-55 cycles min^{-1}, 66-81% suction phase) and ‘slow’ (47 cycles min^{-1}, 43% suction phase) treatments; the ‘fast’ treatment resulted in an increase in teat thickness. ROȘCA et al. (2017) analyzed the effect of different pulsation rates (50, 55, 60 cycles min^{-1}) on the teat-liner contact pressure and found a decreasing contact pressure with increasing pulsation rate. A comparison of seven d-phase duration levels (50 ms, 100 ms, 150 ms, 175 ms, 225 ms, 250 ms, and 300 ms) resulted in a significant reduction in the estimated cross-sectional area of the teat canal at d-phase durations of 50 and 100 ms (UPTON ET AL., 2016). The increase in the b-phase duration from 220 to 800 ms resulted in an increasing incidence of teat end congestion (REINEMANN ET AL., 2008). The duration of the d-phase should be at least 200 ms to reduce teat end lesions (REID AND JOHNSON, 2003).

BLUEMEL ET AL. (2016) found that an extended c-phase during the pulsation cycle decreased the total vacuum per cycle by 1 kPa and increased the opening and closing duration of the liner, so the authors concluded that an extended c-phase indicated gentler milking. A pulsation ratio of 60:40 resulted in higher contact pressure values compared with a pulsation ratio of 50:50 (ROŞCA et al., 2017). In contrast, GLEESON ET AL. (2004) observed no negative effect on teat tissue by widening the pulsation ratio, and FERNEBORG AND SVENNERSTEN-SJAUNJA (2015) also failed to detect negative effects of different pulsation ratios on teat end hyperkeratosis or teat tissue thickness. According to STERRETT ET AL. (2013) an individual quarter pulsation system may reduce teat end hyperkeratosis. A milking system with a sequential pulsation at a rate of 60 cycles min^{-1} and a pulsation ratio of 65:35 resulted in better teat color scores after milking compared with a conventional milking system (ROSE-MEIERHÖFER ET AL., 2014). The expanding force applied to the teat end increased with alternate pulsation compared with simultaneous pulsation (MEIN ET AL., 2003).

The teat cup liner directly transfers the force created by the pressure difference between the pulsation chamber and the liner interior to the teat tissue (HUBAL, 2010). It is the interface between cow teat and the milking system during machine milking and directly affects the condition of the teat and the teat tissue. RASMUSSEN ET AL. (1998) detected an increased frequency of red and blue teats of cows milked with a liner with a higher mouthpiece height. GATES AND SCOTT (1986) found greater compressive loading at the teat end during liner collapse with narrow bore liners. In contrast, widening the liner upper bore dimension increased the degree of changes in teat diameter and teat wall thickness after machine milking (GLEESON ET AL., 2004). DAVIS ET AL. (2001) measured the compressive load applied to the teat by the closed liner and found that it is proportional to the liner wall thickness. The authors also determined a curvilinear relationship between the insertion depth and the compressive teat load. RØNNINGEN AND REITAN (1990) also found a positive correlation between the insertion depth of the teat in the teat cup and the teat end hardness. Liners with softer material, reduced tension, a smaller barrel, and a reduced mouthpiece depth distributed the pressure over a larger area of the teat (TOL ET AL., 2010). CAPUCO ET AL. (2000) determined a mild increase in teat end hyperkeratosis caused by milking with a liner under high tension. Liner compression seemed to influence the recovery rate of teat tissue (SPANU ET AL., 2008). The liner design, which led to a high compressive load and overpressure at the teat end, caused excessive keratin production (HAEUSSERMANN ET AL., 2009). The results of ZUCALI ET AL. (2008) showed that the risk of developing hyperkeratosis increased with the applied pressure to the teat end by the closed liner. In contrast, REINEMANN ET AL. (2008) found reduced teat end congestion with the application of increasing liner compression. Liner overpressure values should be 8-12 kPa to maintain good teat conditions (MEIN AND REINEMANN, 2009). Teat hardness increased, and teat length as well as teat end diameters changed with increasing liner tension force (KRZYŚ ET AL., 2011). TOL ET AL. (2010) found that conventional round liners concentrated the load over two sides of the teat end, triangular-shaped liners led to three spots of pressure concentration around the complete teat (120° separated from each other), and square-shaped liners distributed pressure around the teat. Comparison of conventional and multi-sided concave liners showed a lower incidence of rough teat end hyperkeratosis in teats milked with the concave liner (HAEUSSERMANN ET AL., 2016). LEONARDI ET AL. (2015) found a positive correlation ($R^2 = 0.97$-0.91) between the liner compression and the pressure difference through the liner wall in round liners. The comparison between round and triangular shaped liners regarding their influence on hyperkeratosis resulted in a lower incidence of hyperkeratosis in teats milked with triangular liners (ZUCALI ET AL., 2009). HAEUSSERMANN ET AL. (2011) confirmed these finding. They determined that triangular-shaped liners may reduce the occurrence of hyperkeratosis. SCHUKKEN ET AL. (2006) found a lower frequency of teat ends with cracks and teat end hyperkeratosis in teats milked with square liners compared with teats milked with round liners. PAULRUD ET AL. (2005) detected colder teats after milking with a soft liner compared with a conventional liner and milking with a silicone liner resulted in much lower contact pressure values (ROȘCA et al., 2017). In contrast, TOL ET AL. (2010) did not observe differences in the pressure values for liners made of silicone or rubber. The maximum pressure was always exerted to the teat end by a teat cup liner (MUTHUKUMARAPPAN ET AL., 1994; TOL ET AL., 2010).

Possible techniques to determine the teat-liner interface

Possible techniques to determine the teat-liner interface can be divided into indirect and direct methods. Indirect methods compose teat scoring by visual observation and indirect estimation methods. Sensor-based methods to detect the teat-liner interface using ultrasonography, infrared thermography, or pressure sensors are direct methods.

Teat scoring by visual observations

Several methods are available to evaluate the influence of the milking systems on teat conditions. The basic principle of these methods is the visual observation of the teats before and after milking. MEIN ET AL. (2001) differentiated changes in teat conditions by short-term changes, medium-term changes, and longer-term changes. The short-term changes appear as a reaction of a single milking and included color changes, swelling at or near the teat base, hardness at or near the teat end, and openness of the teat orifice. To evaluate the teat color, a three- or four-step scoring system can be used. The three-step system includes teat colors of normal pink, reddened, and blue (ROSE-MEIERHÖFER ET AL., 2014). The four-step system used by HILLERTON ET AL. (2000) was extended by the color score of pale. Teat color changes could appear 30-60 s after cluster removal, and they could provide hints about faults in the milking machine or the milking management (HILLERTON ET AL., 2000; MEIN ET AL., 2001). ROSE-MEIERHÖFER ET AL. (2014) used a three-step scoring system to evaluate the ring formation at the teat base after milking. Score one indicated a normal teat without swellings, score two indicated a visible ring at the teat base, and score three indicated a visible swelling and a palpable thickened ring formation at the teat base. Medium-term changes in the teat condition are responses to milking that become visible within a few days or weeks. The teat skin condition and vascular damage are medium-term changes (MEIN ET AL., 2001). DE VLIEGHER ET AL. (2003) used a nine-step scoring system to evaluate the effect of the changeover from conventional to automated milking on teat skin. The scores ranged from smooth supple skin without scales, cracks or chapping (score 1) through more severe drying with early cracks present (score 3) to severe skin damage with deep cracks and open ulcerative lesions or scabs (score 5). The gradation of the scores consisted of steps of 0.5. The teat skin condition can also be evaluated with a six-step scoring system (Table 1) according to TIMMS AND MORELLI (2008).

Table 1. The teat skin scoring scale according to TIMMS AND MORELLI (2008)

Teat skin score	Description
0	Teat skin has been subjected to physical injury
1	Teat skin is smooth, soft, and free of any scales, cracks, or chapping
2	Teat skin shows some evidence of scaling, especially when felt
3	Teat skin is chapped. Chapping is present where visible bits of skin are peeling
4	Teat skin is chapped and cracked. Redness, indicating inflammation, is evident
5	Teat skin is severely damaged / ulcerated / open lesions

MEIN ET AL. (2001) categorized the teat skin condition scores as normal (smooth, soft, healthy skin), dry (scaly, flaky or rough skin without cracking), and open lesions. Teat end hyperkeratosis is the most important longer-term change in teat condition. Several scoring systems are available for evaluating teat end hyperkeratosis available. The four-step system described by MEIN ET AL. (2001) is frequently used in literature. The authors divided the hyperkeratosis scores as no ring (N), smooth or slightly rough ring (S), rough (R), and very rough (VR). This system was used to detect the general effect of machine milking on teat end hyperkeratosis (MEIN ET AL., 2003; HAEUSSERMANN ET AL., 2009; ZOCHE-GOLOB ET AL., 2015), the influence of pulsation (STERRETT ET AL., 2013; FERNEBORG AND SVENNERSTEN-SJAUNJA, 2015) and milking vacuum (REINEMANN ET AL., 2001) on teat end hyperkeratosis, and to analyze differences between different milking systems (ROSE-MEIERHÖFER ET AL., 2014). To increase the precision of the scoring system, a five-step scoring system was used in some investigations (CAPUCO ET AL., 2000; GLEESON AND O'CALLAGHAN, 2001; NEIJENHUIS ET AL., 2001b; GLEESON ET AL., 2003b; RUDOVSKY ET AL., 2011). HAEUSSERMANN ET AL. (2016) analyzed the influence of a multi-sided concave liner barrel design on teat end hyperkeratosis. Consequently, the authors evaluated the thickness as well as the roughness of the hyperkeratosis with the help of a four-step and five-step scoring system, respectively. DE VLIEGHER ET AL. (2003) used a nine-step scoring system to evaluate teat end hyperkeratosis. They gradated the scores in steps of 0.5. The sores ranged from smooth teat end and sphincter with no evidence of roughness (score 1) through teat end sphincter is moderately roughened with radial cracks (score 3) to teat end is severely roughened and has a deep irregular callous (score 5). Regardless of the system, scoring should be performed with the help of a light source, gloves should be used, all surfaces of the teat should be examined, and the data should be recorded immediately (HILLERTON, 2005).

Indirect estimation methods

There are several methods to calculate and estimate the teat load caused by a collapsing liner and that are frequently used in the literature. One of these methods is the detection of the Touch Point (TP), which is the required pressure difference to collapse the liner until the opposing walls of the liner barrel first touch each other (SPENCER AND JONES, 2000; SPENCER ET AL., 2007; ZUCALI ET AL., 2008; MEIN AND REINEMANN, 2009; ROȘCA ET AL., 2012; ALEJANDRO ET AL., 2014a). Another method is to calculate the residual vacuum available for massage. It can be calculated by subtracting the required vacuum to collapse the liner from the average vacuum in the claw (MEIN ET AL., 2003; BADE ET AL., 2009; MEIN AND REINEMANN, 2009). The Liner Compression (LC), the mean compressive pressure applied to the tissue of the teat end by the liner during the d-phase of pulsation, is another method that is used (ZUCALI ET AL., 2008; BADE ET AL., 2009; MEIN AND REINEMANN, 2009; ALEJANDRO ET AL., 2014a). Detecting over-pressure (OP), the average compressive pressure applied to the teat end to stop milk flow from the teat, is also used (MEIN ET AL., 2003; NEIJENHUIS ET AL., 2005; MEIN AND REINEMANN, 2009). Further calculation of the proportion of time that milk flows from a teat relative to the proportion of time that milk flow is stopped by the liner as the true milk : rest ratio is a method to estimate the teat load caused by the liner during milking (MEIN ET AL., 2003; MEIN AND REINEMANN, 2009).

Sensor-based methods

In addition to visual observations and indirect estimation methods, sensor-based methods are increasingly used to evaluate the teat-liner interface during milking. These methods are ultrasonography, infrared thermography, and pressure sensors.

Ultrasonography

The inner structure of the udder and teats can be investigated with the help of ultrasonography (SZENCZIOVA AND STRAPAK, 2012). In earlier studies, B-mode ultrasonography with a 5 MHz (AYADI ET AL., 2003b; WEISS ET AL., 2004; CELIK ET AL., 2008; AMBORD AND BRUCKMAIER, 2010; VETTER ET AL., 2014), a 7.5 MHz (NEIJENHUIS ET AL., 2001a; PAULRUD ET AL., 2005; SPANU ET AL., 2008), and a 12 MHz (KUCHLER, 2011; FASULKOV ET AL., 2014) linear probe was often used to determine the influence of milking on the teat tissue condition. The majority of the investigations was conducted using a contact gel (GLEESON ET AL., 2004; KLEIN ET AL., 2005; RAMBABU ET AL., 2008; PORCIONATO ET AL., 2010) and a water bath dipping method (HAMANA ET AL., 1994; NEIJENHUIS ET AL., 2001a; GLEESON ET AL., 2004; SANTOS ET AL., 2004; WEISS ET AL., 2004; KLEIN ET AL., 2005; PAULRUD, 2005; CELIK ET AL., 2008; SPANU ET AL., 2008; SEKER ET AL., 2009; AMBORD AND BRUCKMAIER, 2010; PORCIONATO ET AL., 2010; STOJNOVIĆ AND ALAGIĆ, 2012; VETTER ET AL., 2014), as shown in Figure 2. SANTOS ET AL. (2004) compared four different methods of ultrasonic performance (direct contact, direct contact with standoff, water bath, liquid pressure). RAMBABU ET AL. (2008) compared the methods of direct contact, gel application, water bath, and standoff. In both studies, the water bath method was considered the ideal method to identify the teat anatomy.

Figure 2. Ultrasonic measurement of the bovine teat using the water bath method (GLEESON ET AL., 2004)

Ultrasonic measurements were used to generally determine the features and sizes of the teat structure in cows (FASULKOV ET AL., 2014) and buffaloes (RAMBABU ET AL., 2009) and to visualize different influences on the bovine teat (KHOL ET AL., 2006). WEISS ET AL. (2004)

used ultrasonic imaging to demonstrate possible relationships between teat anatomy and functionality. AYADI ET AL. (2003b) used ultrasonography to estimate the teat cistern size and milk storage at different milking intervals as well as to investigate the response of cows to omit one milking per week (AYADI ET AL., 2003a). The effect of teat morphology on mastitis was examined with the help of ultrasonography as well (HAMANA ET AL., 1994; KLEIN ET AL., 2005; SEKER ET AL., 2009). CELIK ET AL. (2008) used ultrasonography to evaluate age-related changes in the teat canal. Ultrasonic imaging is also used to determine the influence of milking and milking technique on teat anatomy. GLEESON ET AL. (2004) determined the effect of liner design, pulsator settings, and vacuum level on teat tissue changes. Ultrasonography was used to analyze the influence of four different milking treatments on the teat wall thickness (SPANU ET AL., 2008). NEIJENHUIS ET AL. (2001a) investigated the recovery time of teat tissue after milking using ultrasonic measurements. Ultrasonography is usable to determine daily changes in teat parameters caused by machine milking (STOJNOVIĆ AND ALAGIĆ, 2012). KUCHLER (2011) analyzed the influence of milking on blood flow and teat morphology with the help of ultrasonography. Ultrasonic imaging can also be used to monitor the effect of the liner type and overmilking on teat tissue recovery (PAULRUD ET AL., 2005). AMBORD AND BRUCKMAIER (2010) used ultrasonography to study the effects of different milking systems on milking characteristics and teat tissue congestion. VETTER ET AL. (2014) investigated the effect of a latency period after pre-stimulation and before teat cup attachment, as well as the influence of a periodic vacuum reduction on the teat condition, with the aid of B-mode ultrasound. PORCIONATO ET AL. (2010) used ultrasonic measurements to evaluate the relationship between milk flow, teat morphology, and subclinical mastitis prevalence in Gir (zebu breed) cows.

Infrared thermography and digital imaging

Infrared thermography is a non-invasive technique to visualize thermal profiles (KUNC ET AL., 2007). An infrared camera measures the emitted infrared radiation from an object and uses this information to create thermograms (KNÍŽKOVÁ ET AL., 2007). In earlier studies, the influence of the machine milking on the teat temperature was investigated with the help of infrared thermography (Figure 3). MAYNTZ (1990) compared the effect of linerless and conventional milking on teat temperature with the aid of infrared imaging. An infrared camera was used to investigate the dynamics of surface temperature changes in response to vacuum changes and the liner type (KUNC ET AL., 1999). ORDOLFF (2000) used infrared thermography to compare the influence of conventional and automatic milking on the teat load. The influence of calf-suckling and machine milking on the teat temperature was investigated by KUNC ET AL. (2002). PAULRUD ET AL. (2005) studied the influence of liner characteristics and overmilking on teat temperature using infrared thermography. Thermographic measurements can be used to analyze whether different milking equipment affect blood circulation in the teat during milking (VEGRICHT ET AL., 2007). KUNC ET AL. (2011) studied the influence of the vacuum level during milking on the bovine teat using an infrared camera.

Figure 3. Example udder and teat temperature video recording (VEGRICHT ET AL., 2007)

The use of digital imaging to evaluate the teat condition could be a first step to making the teat condition scoring more objective. ZECCONI ET AL. (2005) used a digital camera to test whether this objective method is feasible under field conditions and whether it is comparable to other methods. A camera was used to obtain a 2D image of the teat to determine its length and diameter (ZWERTVAEGHER ET AL., 2011). The variance of the teat dimensions and the cow- and quarter level factors associated with the teat dimension were identified using this 2D device (ZWERTVAEGHER ET AL., 2012). The 2D device measured both the teat length and diameter in one measurement and allowed efficient and rapid collection of data (ZWERTVAEGHER ET AL., 2013). Thus, the teat condition could be determined more objectively.

Pressure sensors

In several studies, the usability of pressure sensors to measure the pressure between a teat and the teat cup liner was tested. GATES AND SCOTT (1986) used a miniature pressure transducer that was placed in a brass case. A small copper pipe was soldered to the brass case to flood the transducer with water. An elastic diaphragm was glued on top of the transducer to close it (Figure 4).

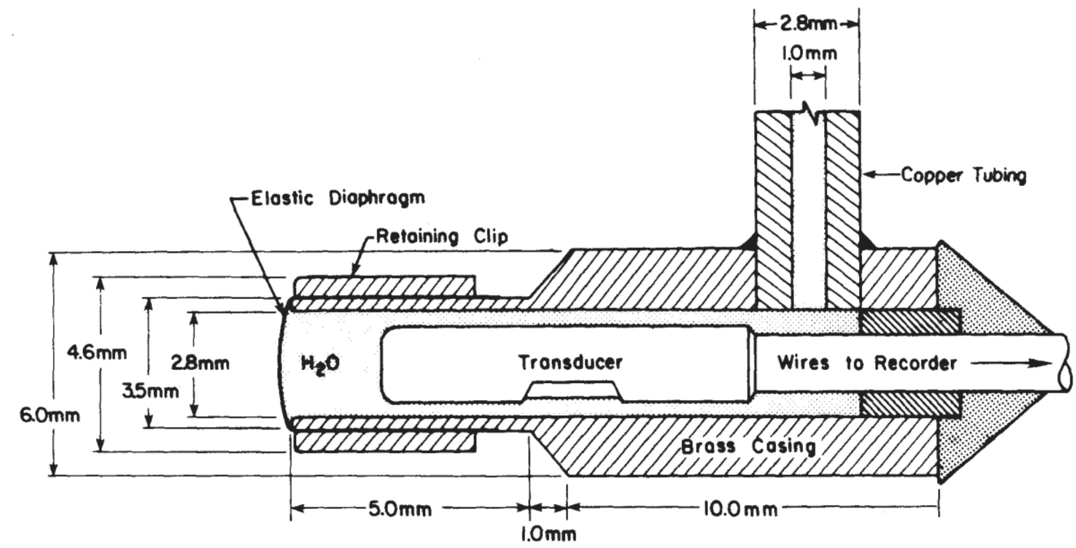

Figure 4. Schematic of the teat load transducer according to GATES AND SCOTT (1986)

MUTHUKUMARAPPAN ET AL. (1994) tested the usability of thin-film force sensors to measure the compressive load applied to the teat by different teat cup liners. The authors found both sensors unsatisfactory. One sensor showed significant error caused by bending, and the other sensor had insufficient sensitivity. ADLEY AND BUTLER (1994) used a load cell-containing aluminum teat to measure the forces applied by a teat cup liner (Figure 5). The teat they used consisted of three hollow cylindrical sections. One of these sections had a radial hole in which was fitted a piston. The inner end of this piston was in contact with a miniature load cell inside the teat when pressure was applied. The other cylindrical section could be removed to shorten the teat or to interchange the sections to change the position of the load cell.

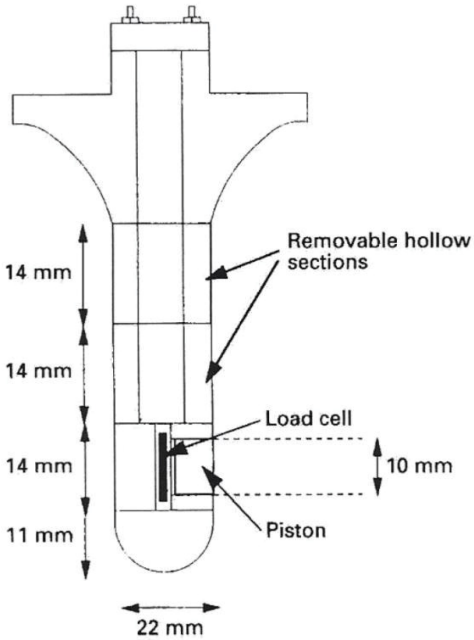

Figure 5. The artificial teat, including the location of the load cell, according to ADLEY AND BUTLER (1994)

DAVIS ET AL. (2001) developed a device similar to the teat sensor used by ADLEY AND BUTLER (1994), but their device deformed much more such as live teats (Figure 6). Therefore, they mounted a miniature load cell on a steel plate. The sensing surface was thus flush with the surface of the steel plate. The sensor was covered using natural gum rubber and a gel-like material.

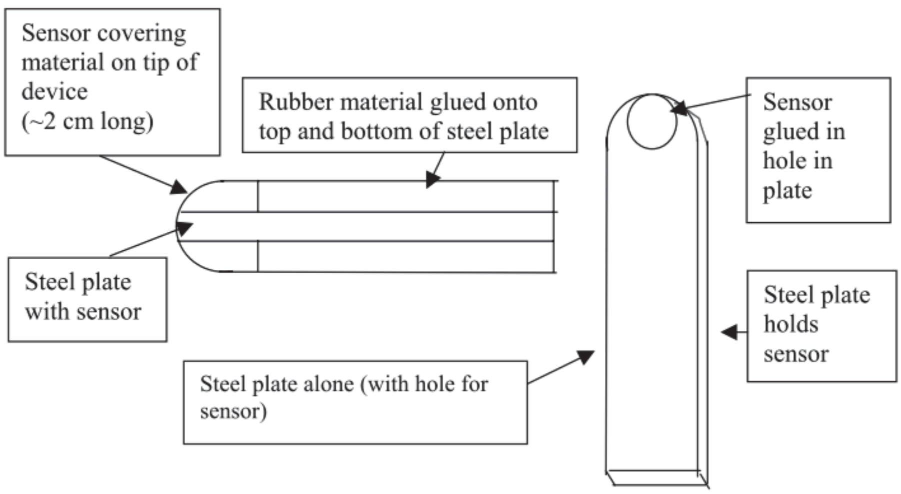

Figure 6. Compressive teat load measurement device according to DAVIS ET AL. (2001)

TOL ET AL. (2010) investigated the teat-liner interface with the aid of a flexible pressure-sensitive layer. The layer included carbon particles and was attached to a resin film through which electrodes faced each other. If pressure was applied to the resin film, the distance between the carbon particles was reduced, the tunneling phenomenon occurred and the electrical resistance between the electrodes decreased. LEONARDI ET AL. (2015) used an artificial teat sensor adapted from DAVIS ET AL. (2001). The authors mounted their force sensor on a flat plastic plate with a 9.5-mm-radius rounded end as the active area of the force sensor. They used a FlexiForce sensor (FlexiForce B201 Sensors, Tekscan Inc., South Boston, MA), which is an ultra-thin sensor that measures the force between two surfaces. The measuring principle of this sensor is based on piezoelectric technology (ENGLUND and PATCHING, 2009). According to the manufacturer, the FlexiForce sensor consists of two substrate layers composed of polyester. Silver is applied on each layer as conductive material, followed by a layer of pressure-sensitive ink. The silver circle is the active measuring area. If pressure is applied, the silver extends from the sensing area to the connectors at the other end of the sensor. The end of the sensor of LEONARDI ET AL. (2015) was covered by a cylinder with an end molded from silicone (Shore A hardness 10). According to the authors, this sensor is usable only for round liners. ROȘCA et al. (2017) used a pressure recording system consisting, among other components, of an artificial teat (according to the ISO 6690) equipped with a force transducer (FlexiForce A201, Tekscan Inc., South Boston, MA), with a measuring principle similar to the sensor used by LEONARDI ET AL. (2015), to evaluate the teat-liner contact pressure and its dependence on the liner type, pulsation rates, and pulsation ratios.

As methods commonly used to determine the teat load caused by a collapsing liner are very subjective or use indirect estimation and because the tested sensor-based methods are very complex to use or have shown limited usability, measurement of the static pressure distribution and magnitude with the aid of red color density variation was used to investigate the teat load due to liner collapse. The pressure measurement method that was applied is described in detail in Chapter 2.

Objectives and hypotheses of the thesis

The primary objective of the present thesis was to investigate the teat-liner interface with the help of a new method. Therefore, measurement of the static pressure distribution and magnitude with the aid of red color density variation was used to determine the teat load caused by a collapsing liner under specific conditions. The following specific objectives of the dissertation were stated:

- Determination of the usability of measurement of the static pressure distribution and magnitude with the aid of red color density variation to measure the teat load caused by a collapsing liner
- Investigation of the influence of different milking settings on the direct teat load due to a collapsing liner
- Detection of the effect of different teat cup liners on the teat load caused by liner collapse

The following hypotheses were established to reach these objectives:

1. Measurement of the static pressure distribution and magnitude with the aid of red color density variation can be used to directly measure the pressure between an artificial teat and the collapsing liner
2. There are significant differences between different adjustments of the machine vacuum, the pulsation rate, and the pulsation ratio regarding the directly measured teat load caused by liner collapse
3. There are significant differences between teat cup liners with different designs and made of different materials with regard to the directly measured teat load due to a collapsing liner

In the following chapters, investigations to confirm / reject these hypotheses are listed. In addition, the results of individual studies are discussed coherently.

Chapter 2

The Usability of a Pressure-Indicating Film to Measure the Teat Load Caused by a Collapsing Liner

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Communication

The Usability of a Pressure-Indicating Film to Measure the Teat Load Caused by a Collapsing Liner

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Abstract: Prevention of damage to the teat and mastitis requires determination of the teat load caused by a collapsing liner. The aim of this study was to test a pressure-indicating film designed to measure the pressure between a collapsing liner and artificial teats. The Ultra Super Low and the Extreme Low pressure-indicating films were tested on two types of artificial teat. The experiments were performed with a conventional milking cluster equipped with round silicone liners. For each teat and film type, 30 repetitions were performed. Each repetition was performed with a new piece of film. Kruskal-Wallis tests were performed to detect differences between the pressure values for the different teats. The area of regions where pressure-indication color developed was calculated to determine the most suitable film type. Both film types measured the pressure applied to both artificial teats by the teat cup liner. Thus, the pressure-indicating films can be used to measure the pressure between a collapsing liner and an artificial teat. Based on the results of the present investigation, a pressure-indicating film with the measurement ranges of both film types combined would be an optimal tool to measure the overall pressure between an artificial teat and a collapsing liner.

Keywords: teat load; liner collapse; pressure-indicating film; artificial teat; machine milking

1. Introduction

The teat cup liner is the interface between the teat of a dairy cow and the milking machine. A milking system that works improperly can damage the teat and can increase the risk of udder infections. To evaluate the influence of machine milking on the teat condition, various scoring systems evaluating teat color, swellings, ring formation at the teat base, and hyperkeratosis are used [1,2]. However, these methods are subjective. Therefore, methods to detect the pressure between the teat and a collapsing liner have been developed. One such method frequently used in literature is the calculation of the touch point [3–8], the residual vacuum available for massage [4,9,10], the liner compression [3,4,8,9], the over-pressure [4,10,11], and the true milk:rest ratio [4,10]. In several studies, the usability of pressure sensors to measure the pressure between a teat and the teat cup liner was tested. Muthukumarappan et al. [12] tested the usability of thin-film force sensors to measure the compressive load applied to the teat by different teat cup liners. The authors found both sensors unsatisfactory. One sensor showed significant error caused by bending and the other sensor had insufficient sensitivity. Adley and Butler [13] used a load cell-containing aluminum teat to measure the forces applied by a teat cup liner. The teat they used consisted of three hollow cylindrical sections. One of these sections had a radial hole in which a piston was fitted. The inner end of this piston was in contact with a miniature load cell inside the teat when pressure was applied. The other cylindrical section could be removed to shorten the teat or to interchange the sections to change the position of the load cell. Davis et al. [14] developed a device similar to the teat sensor used by Adley and Butler [13], but their device deformed much like live teats. Therefore, they mounted a miniature load cell on a steel plate. The sensing surface was thus flush with the surface of the steel plate. The sensor was covered using natural gum rubber and a gel-like material. Tol et al. [15] investigated the teat-liner interface with the help of a flexible pressure-sensitive layer. The layer included carbon particles and was attached to a resin film through which electrodes faced each other. If pressure was applied to the resin film, the distance between the carbon particles was reduced, the tunneling phenomenon occurred and the electrical resistance between the electrodes decreased. Leonardi et al. [16] used an artificial teat sensor adapted from Davis, Reinemann and Mein [14]. The authors mounted their force sensor on a flat plastic plate with a 9.5-mm-radius rounded end as the active area of the force sensor. The end of the sensor was covered by a cylinder with an end molded from silicone (Shore A hardness 10). According to the authors, this sensor is useful only for round liners.

The Prescale pressure-indicating film by Fujifilm (KAGER Industrieprodukte GmbH, Dietzenbach, Germany) is used to measure pressure, pressure distribution, and pressure balance. The Prescale pressure-indicating films are available in mono- and two-sheet types. The mono-sheet type has a polyester base containing the color-developing materials. In contrast, the two-sheet film consists of a color-forming layer and a color-developing layer. When pressure is applied to the Prescale film, the microcapsules are broken, and the color-forming material reacts with the color-developing material. As a result, red patches appear on the film, and the density of the red color indicates several levels of pressure. The Prescale pressure-indicating films measure pressures between 0.05 MPa and 300 MPa [17]. They do not support shear stress [18], and shear stress can alter the color intensity measured by the film [19].

As the methods commonly used to detect the teat load caused by the liner use indirect estimation, and as the tested sensors have shown limited usability, the aim of this study was to determine whether the Prescale pressure-indicating films developed by Fujifilm can be used to measure the teat load caused by liner collapse.

2. Materials and Methods

2.1. Study Design and Data Collection

The Ultra Super Low (Film 1) and the Extreme Low (Film 2) films (Prescale by Fujifilm, KAGER Industrieprodukte GmbH) were tested. Both are two-sheet film types with a thickness of 0.1 mm, and both consist of an A-film (Side A) and a C-film (Side C). Side A is composed of a polyester base and a microencapsulated color-forming layer. The components of Side C are a color-developing layer and a polyester base. To measure an applied pressure, both sides must adjoin each other at the rough sides. If the sides do not adjoin each other while a pressure is applied, no reaction and therefore no color change takes place. The pressure ranges are 0.2–0.6 MPa for Film 1 and 0.05–0.2 MPa for Film 2.

Two experiments were conducted in this investigation. To test whether the two pressure-indicating films measured the load of the liner in the teat cup during liner collapse, two types of pressure-indicating film were tested on an artificial, stiff plastic teat in the first experiment (E1). The plastic teat was 54 mm in length with an average diameter of 21.5 mm. To test whether the pressure-indicating films measured the pressure between two flexible objects, both types of pressure-indicating film were tested on a flexible, silicone rubber teat in the second experiment (E2). This teat had a length and a mean diameter of 56 mm and 21 mm, respectively. According to the manufacturer, the silicone rubber had a Shore A hardness 25, a density of 1.16 $g \cdot cm^{-3}$ at a temperature of 23 °C, a tensile strength of 5.00 $N \cdot mm^{-2}$, an ultimate elongation of 350%, a tear resistance of more than 20 $N \cdot mm^{-1}$, and a linear shrinkage of 0.5%. The plastic and silicone teats are shown in Figure 1.

Figure 1. The plastic teat (**left**) and the silicone teat (**right**) used in this investigation.

All experiments were performed in the laboratory milking parlor of the Leibniz Institute for Agricultural Engineering and Bioeconomy. A conventional milking cluster equipped with round silicone liners was used to measure the teat load caused by the liner. The milking cluster consisted of four teat cups, each with a short milk tube and a short pulse tube. The short milk tubes joined in a claw where the milk of the whole udder normally flows together. The IQPro liner by GEA (GEA Group Aktiengesellschaft, Düsseldorf, Germany) was used in this investigation. The liner had a shaft diameter of 24 mm, a mouthpiece diameter of 21 mm, and a head diameter of 58 mm. All measurements were taken in the same teat cup. In order to test whether the measurement values are repeatable the measurements were carried out under constant conditions. Therefore, the machine vacuum was adjusted at 40 kPa. A pulsation rate of 60 min^{-1} and a pulsation ratio of 60:40 were used. The pressure-indicating film was cut into 35 mm × 45 mm pieces, and the pieces were attached at the teat with tape. To ensure that all film pieces were attached in the same position, the teats were marked (Figure 1). The teat with the pressure-indicating film was inserted into the teat cup, and the liner was opened and closed for 30 s so that the liner collapsed 30 times. The teat was aligned in the teat cup with the collapsed liner, and the sides of the pressure-indicating film were pressed together (Figure 2). For both types of teat and film, 30 repetitions were performed. Each repetition was done with a new piece of film. There was no milk or water flow involved in the experiments because the artificial teats were not hollow and thus not suitable to involve milk or water flow.

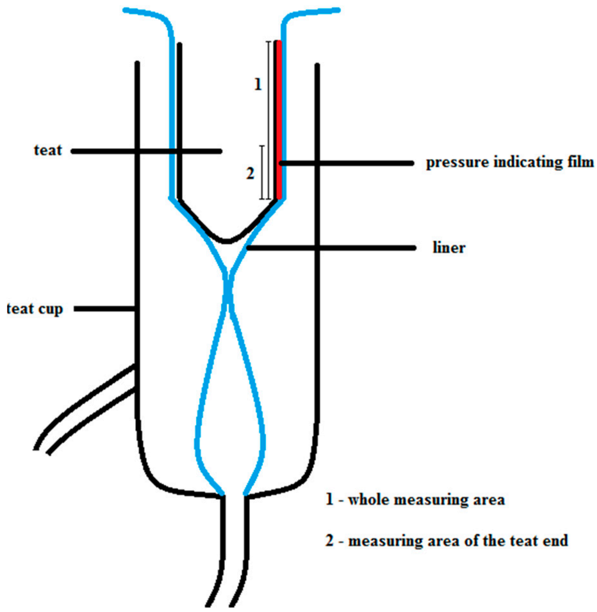

Figure 2. Schematic drawing of the position of the teat equipped with the pressure-indicating film.

After the measuring procedure, the C-sides of the films were visualized with a scanner (Epson Perfection V37/V370 Photo, KAGER Industrieprodukte GmbH) and analyzed with the FPD-8010E software by Fujifilm (KAGER Industrieprodukte GmbH). This software was used to analyze the six parameters proportionately within the film's pressure-detection range (effective rate, ER, in %), the surface area on which the color was generated (pressed area, PA, in mm^2), the mean pressure on the area on which the color was generated (average pressure, AP, in MPa), the maximum pressure of the area on which the color was generated (maximum pressure, MP, in MPa), the product of the pressurization surface area and average pressure (load, L, in N), and the measured area (MA, in mm^2). In this investigation, the values of AP, MP, and the colored area (CA) were used to evaluate the usability of the Prescale pressure-indicating film to measure the teat load caused by a collapsing liner. CA was calculated as follows:

$$CA = PA/MA \tag{1}$$

where CA is colored area in %; PA is pressed area in mm^2; and MA is measured area in mm^2.

AP, MP, and CA were calculated for the whole area of the film piece as well as for the area of the teat end. The area of the teat end was defined as the area of the lower third of the barrel of the artificial teats. These calculations were performed for each film and teat.

2.2. Pretest: Influence of Bending and Negative Pressure on the Measurements

To investigate the influence of bending on the pressure-indicating film, the films were attached at the teats for 2 min. Two attachment methods were tested. The pressure-indicating films were directly attached with Side A as well as with Side C on the teat. For each teat, film type, and attachment method five repetitions were done, each repetition with a new piece of film. AP, MP, and CA were calculated.

To analyze the influence of negative pressure on the measuring results, a mobile milker (Minimelker, schlauerbauer Melktechnik GmbH, Leipzig, Germany) was used. The pressure-indicating film was attached inside at the bottom of the milk can of the mobile milker and the teat cups were closed with the help of plugs. The machine pressure was adjusted at −41 kPa and the film was exposed to the negative pressure for 30 s. For each film type five repetitions were done, each repetition with a new film piece. AP, MP, and CA were analyzed.

2.3. Statistical Analyses

Data were analyzed with the SAS software package 9.4 (SAS Institute Inc., Cary, NC, USA). The UNIVARIATE procedure was used to calculate descriptive statistics for AP and MP. Kruskal-Wallis-tests were performed to estimate differences between the two artificial teats and between areas regarding AP and MP using the NPAR1WAY procedure because the distribution of the measurement values of both traits was not symmetrical. The null hypothesis was that there were no differences between the teats and the areas.

The GLIMMIX procedure was used for a one-way ANOVA to examine the percentage of CA for each teat and film type. As the observations were percentage values, a binomial distribution with a logit link function was used. The linear predictor η is calculated as follows:

$$\eta_i = \mu + F_i + \varepsilon_i \tag{2}$$

where μ is the general mean; F_i is the fixed effect of film i (Film 1, Film 2); and ε_i is the residual. The null hypothesis was that there were no differences between the tested films regarding the color-developing area.

To analyze the influence of bending and negative pressure on the pressure values measured by the pressure-indicating film, descriptive statistics for AP and MP were calculated using the UNIVARIATE procedure. The GLIMMIX procedure was used to examine the percentage of CA for each teat and film type. A t-test was carried out to investigate differences between the attachment methods of the films.

The null hypothesis was that there were no differences between the methods. All tests were carried out at a significance level of 0.05.

3. Results

3.1. Influence of Liner Collapse on Teat Load

The median, minimum, 25% quantile, 75% quantile, and maximum values of AP and MP for both teats, tested areas, and film types are given in detail in Table 1.

Table 1. Median, minimum, 25% quantile (Q1), 75% quantile (Q3), and maximum values of average pressure (AP) and maximum pressure (MP) of both teats, tested areas, and film types.

Teat	Area	Film-Type	Variable	Median	Minimum	Q1	Q3	Maximum
Plastic	Whole	Film 1	AP	0.22	0.20	0.21	0.22	0.23
			MP	0.64	0.47	0.64	0.64	0.64
		Film 2	AP	0.08	0.07	0.07	0.08	0.08
			MP	0.23	0.21	0.23	0.23	0.24
	Teat end	Film 1	AP	0.26	0.22	0.25	0.27	0.33
			MP	0.64	0.46	0.64	0.64	0.64
		Film 2	AP	0.10	0.09	0.10	0.11	0.11
			MP	0.23	0.21	0.23	0.23	0.24
Silicone	Whole	Film 1	AP	0.22	0.20	0.22	0.23	0.27
			MP	0.64	0.52	0.64	0.64	0.64
		Film 2	AP	0.08	0.08	0.08	0.09	0.10
			MP	0.21	0.19	0.20	0.22	0.23
	Teat end	Film 1	AP	0.25	0.21	0.23	0.27	0.29
			MP	0.64	0.44	0.58	0.64	0.64
		Film 2	AP	0.09	0.08	0.09	0.10	0.12
			MP	0.21	0.19	0.20	0.22	0.23

In E1, both film types measured the pressure and the pressure distribution between the teat cup liner and the plastic teat. For Film 1, AP and MP were 0.22 MPa and 0.63 MPa for the whole film piece and 0.26 MPa and 0.63 MPa for the teat end, respectively. The pressure values of Film 2 were between 0.08 MPa and 0.23 MPa for the whole film piece and between 0.09 MPa and 0.21 MPa for the teat end. Figure 3 shows an example of the pressure level and the pressure distribution for Film 1 and Film 2.

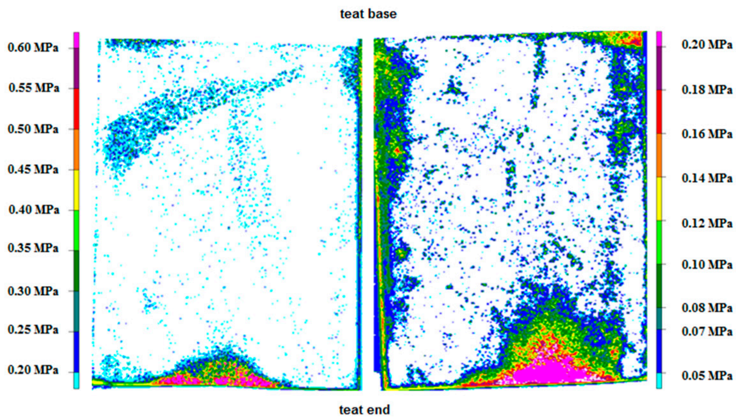

Figure 3. Pressure levels and pressure distribution on a plastic teat caused by the collapsing liner measured with Film 1 (**left**) and Film 2 (**right**).

In E2, Film 1 and Film 2 measured the pressure and the pressure distribution between the liner and a silicone teat (Figure 4). The pressure values of Film 1 and the whole film piece were 0.22 MPa and 0.62 MPa for AP and MP, respectively. For the teat end, AP and MP were 0.25 MPa and 0.61 MPa for Film 1, respectively. For Film 2, the measurements were 0.09 MPa (AP) and 0.21 MPa (MP) for the whole film piece, as well as for the teat end.

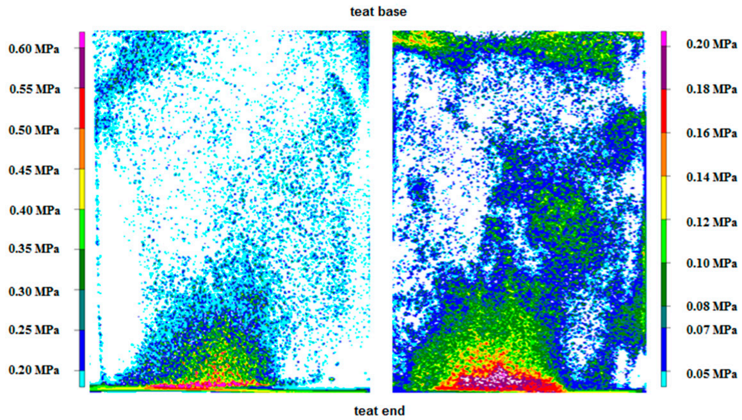

Figure 4. Pressure levels and pressure distribution on a silicone teat caused by the collapsing liner measured with Film 1 (**left**) and Film 2 (**right**).

The results of the Kruskal-Wallis tests show significant differences between teats regarding the values of AP and MP. These differences depend on the measuring area and the film type. The pressure values of Film 1 show significant differences between both artificial teats for AP of the whole area ($p = 0.0397$) and for MP of the teat end area ($p = 0.023$). The pressure values of MP of the teat end were higher for the plastic teat. Regarding AP of the whole area, the pressure was higher on the teat made of silicone. In comparison, with Film 2, the pressure values of the plastic teat were higher than those of the silicone teat for MP of the whole area ($p < 0.0001$), as well as for AP ($p = 0.0005$) and MP ($p < 0.0001$) of the teat end area. The values of AP of the whole area were higher for the silicone teat ($p = 0.0001$).

Significant differences between measuring areas could be found as well. The values of AP of both Film 1 ($p < 0.0001$; $p < 0.0001$) and Film 2 ($p < 0.0001$; $p = 0.003$) were higher in the teat end area than in the whole area for both artificial teats (plastic and silicone, respectively). No significant differences could be found for MP.

The differences in the color-developing area between teats and film types are given in Table 2.

Table 2. Mean and lower and upper 95% confidence interval (CI) for the mean of the colored area (%) of all tested teats, film types, and areas.

Teat	Film Type	Area	Mean	Lower 95% CI of Mean	Upper 95% CI of Mean
Plastic	Film 1	Whole	13.5	5.1	31.2
		Teat end	18.8	8.3	37.1
	Film 2	Whole	36.7	21.4	55.3
		Teat end	46.4	29.3	64.3
Silicone	Film 1	Whole	21.7	10.3	40.2
		Teat end	24.0	11.8	42.6
	Film 2	Whole	75.1	56.4	87.2
		Teat end	88.3	70.7	95.9

With the plastic teat, on Film 1, color developed on 13.5% of the whole area and on 18.8% of the teat end area. The color-developing area of Film 2 was 36.7% of the whole area and 46.4% of the teat end area.

On the silicone teat, the color-developing area was 22% of the whole area on Film 1 and 75% on Film 2. On the teat end area, color developed on 24% of Film 1 and on 88% of Film 2. Thus, more color developed on Film 2 and in the teat end area, indicating that more pressure was applied on the teat end.

3.2. Pretest: Influence of Bending and Negative Pressure on the Measurements

Table 3 shows the influence of bending on the pressure-indicating film by artificial teat, attachment method, and film type.

Table 3. Colored area (CA), average pressure (AP), and maximum pressure (MP) with 95% confidence intervals (CI) by artificial teat, side of attachment (Side A or Side C directly on the teat), and film type after bending of the pressure-indicating films.

Teat	Side	Film Type	CA (%)	CI of the Mean		AP (MPa)	CI		MP (MPa)	CI	
				Lower	Upper		Lower	Upper		Lower	Upper
Plastic	A	Film 1	1.1	0.000	99.5	0.17	0.16	0.17	0.35	0.30	0.41
		Film 2	9.9	0.35	77.6	0.06	0.06	0.07	0.15	0.13	0.17
Silicone	A	Film 1	3.4	0.01	91.3	0.17	0.17	0.18	0.37	0.32	0.45
		Film 2	10.4	0.39	77.3	0.06	0.06	0.06	0.14	0.11	0.15
Plastic	C	Film 1	3.8	0.02	89.8	0.18	0.17	0.18	0.42	0.39	0.44
		Film 2	10.8	0.43	77.1	0.06	0.06	0.07	0.16	0.14	0.23
Silicone	C	Film 1	3.2	0.009	92.2	0.18	0.17	0.19	0.44	0.34	0.55
		Film 2	4.2	0.003	88.2	0.06	0.06	0.07	0.14	0.12	0.16

Depending on artificial teat and film type, CA ranged between 1.1% and 10.4% when Side A was attached directly to the teat. The pressure values were between 0.06–0.17 MPa for AP and 0.14–0.37 MPa for MP. When Side C was attached directly to the teat, CA was between 3.2% and 10.8%. With this attachment method, the measured pressure for AP and MP was 0.06–0.18 MPa and 0.14–0.44 MPa, respectively. No significant differences between the attachment methods and their influence on the measurement results were found by the t-test.

The results regarding the influence of negative pressure on the measurements of the pressure-indicating film show that on Film 1, color developed on 0.03% of the film area. The pressure values of Film 1 for AP and MP were 0.16 MPa and 0.22 MPa, respectively. On Film 2, color developed on 0.01% of the film area. The measured values were 0.05 MPa for AP and 0.09 MPa for MP.

4. Discussion

Depending on artificial teat, film type, and measuring area, the pressure applied due to a collapsing liner ranged between 0.07 MPa (70 kPa) and 0.64 MPa (640 kPa). These pressure values are much higher than those found in other investigations. The pressure measured by Tol, Schrader and Aernouts [15] was 99–180 kPa at the teat end. Muthukumarappan et al. [20] measured a pressure of 18–35 kPa between a teat and a collapsing liner. Depending on the vacuum in the short milk tube and the liner design, Leonardi, Penry, Tangorra, Thompson and Reinemann [16] found pressure values between 20 kPa and 34 kPa. Davis, Reinemann and Mein [14] detected pressures of 20–41 kPa between the liner and teat. The artificial teats used in the present investigation could explain why the pressure values measured in this investigation are higher: in the other investigations the artificial teats were hollow and made of silicone [15]; our artificial teats were not hollow. However, the silicone teat used in the present investigation was very stiff. In future investigations, a hollow silicone teat will be used to detect the pressure caused by a collapsing liner. Differences in material offer an additional explanation. Adley and Butler [13] used a teat made of aluminum and the artificial teat of Muthukumarappan, Reinemann and Mein [12] was liquid-filled, flexible, not extensible and made of a plastic teat cup plug, a surgical glove finger, and a cloth glove finger. The artificial teat of Davis, Reinemann and Mein [14] contained natural gum rubber or a gel-like material. Leonardi, Penry, Tangorra, Thompson and Reinemann [16] used a silicone rubber with a Shore A hardness of 10. In the present investigation, a silicone rubber with a Shore A hardness of 25 was used.

With both tested teats, more pressure was found on the teat end compared to the whole teat. These results agree with those of Tol, Schrader and Aernouts [15]. They had found that the maximum pressure was always exerted on the teat end. The study of Muthukumarappan, Reinemann and Mein [12] showed that the maximum pressure was applied within 1 or 2 mm of the teat end. They detected a progressive decrease in the applied pressure over the upper 3 or 4 mm of the teat end.

Film 2 was more suitable as a tool to measure the pressure between a collapsing liner and both artificial teats than Film 1 was because more color developed on Film 2. The specific pressure range of Film 2 (0.05–0.2 MPa) could explain this finding. The analyses of the film types showed white pixels in the area of the teat end, possibly as a result of the pressure range of the film types. The pressure seems to be higher or lower at these points than the films can measure. Thus, the pressure ranges of neither film alone were sufficient to measure the overall load between the collapsed liner and the artificial teats. Therefore, a pressure-indicating film with the pressure range of both types of film would be a useful tool to measure the pressure between these artificial teats and the liner.

The influence on the measurement results of bending and negative pressure on the pressure-indicating film was not significant.

5. Conclusions

In general, both Film 1 and Film 2 measured the pressure and the pressure distribution between either a plastic teat or a silicone teat and a collapsing liner. The pressure-indicating film is not influenced by bending or negative pressure. It can be used to detect differences between teats regarding the applied pressure as well. Thus, the Prescale pressure-indicating film can be used to measure the pressure between a collapsing liner and the artificial teats. Based on the results of this investigation, a pressure-indicating film that includes the measured ranges of both film types (0.05–0.6 MPa) would be useful. However, the usefulness of the pressure-indicating films to measure the pressure between two flexible objects remains to be determined, and, therefore, further studies are required. The influence of milking settings and different liner types on the teat load will be examined as well.

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Abbreviations

AP	average pressure
CA	colored area
CI	confidence interval
E1	experiment one
E2	experiment two
ER	effective rate
Film 1	Ultra Super Low Prescale pressure-indicating film
Film 2	Extreme Low Prescale pressure-indicating film
L	load
MA	measured area
MP	maximum pressure
PA	pressed area
Q1	25% quantile
Q3	75% quantile
Side A	the A-film of the pressure-indicating film
Side C	the C-film of the pressure-indicating film
STD	standard deviation

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Chapter 3

The Influence of Different Milking Settings on the Measured Teat Load Caused by a Collapsing Liner

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Chapter 4

A Pressure-Indicating Film to Determine the Effect of Liner Type on the Measured Teat Load Caused by a Collapsing Liner

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Article

The Use of a Pressure-Indicating Film to Determine the Effect of Liner Type on the Measured Teat Load Caused by a Collapsing Liner

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Abstract: During milking the teat cup liner is the interface between the teat of a dairy cow and the milking system, so it should be very well adapted to the teat. Therefore, the aim of the present study was to determine the effect of liner type on the directly measuring teat load caused by a collapsing liner with a pressure-indicating film. The Extreme Low pressure-indicating film was used to detect the effect of six different liners on teat load. For each liner, six positions in the teat cup were specified, and six repetitions were performed for each position with a new piece of film each time. Analysis of variance was performed to detect differences between the six liners, the positions within a liner, and the measuring areas. The pressure applied to the teat by a liner depends on the technical characteristics of the liner, especially the shape of the barrel, and for all tested liners, a higher teat load was found at the teat end. In conclusion, with the help of pressure-indicating film, it is possible to determine the different effects of liner type by directly measuring teat load due to liner collapse.

Keywords: sensor-based detection; pressure sensor; teat load; liner collapse; machine milking

1. Introduction

During machine milking, the teat cup liner is the interface between the teat of a dairy cow and the milking system; it transfers the force created by the pressure difference between the pulsation chamber and the interior of the liner directly to the teat tissue [1]. While the teat of a dairy cow is robustly constructed and well adapted to shear stress [2], machine milking can worsen the condition of the teat and teat tissue [3–5]. Therefore, it is important that the liner is very well adapted to the teat.

The most commonly used method to detect the impact of liner type is to visually evaluate teat condition based on teat color, swelling, ring formation at the teat base, and teat-end hyperkeratosis [3,6–10].

In addition to visually observing teat condition, sensor-based determination of the influence of liner type on the teat load caused by liner collapse can be performed with several measuring devices. Paulrud et al. [11] used infrared thermography as well as ultrasonography to monitor the influence of liner type on teat temperature and teat traits such as the teat cistern wall, teat cistern diameter, and teat canal length. The ultrasonography was also used by Gleeson et al. [12] and Gleeson, O'Callaghan, Meaney and Rath [8] to investigate differences in teat traits caused by different liners. Several studies have attempted to detect the influence of liner type on the teat load with the help of different pressure-sensitive sensors. Davis et al. [13] measured the compressive load applied to the teat by the closed liner using an artificial teat equipped with a miniature load cell and found that the compressive load of a liner is proportional to the thickness of the liner wall; the authors determined a curvilinear relationship between the insertion depth and the compressive teat load as well. Tol et al. [14] investigated the teat-liner interface using a flexible pressure-sensitive layer and found that conventional round liners concentrated the load over two sides of the end of the teat. In contrast, liners with softer material, reduced tension, a smaller barrel, and reduced mouthpiece depth distributed the pressure over a larger area of the teat, but the maximum pressure was always exerted at the teat end. Leonardi et al. [15] used an artificial teat sensor adapted from Davis, Reinemann and Mein [13] to estimate liner compression, and the round liner compression was positively correlated ($R^2 = 0.97 - 0.91$) with the pressure difference through the liner wall. According to these authors, this sensor is only useful for round liners.

As the methods commonly used to detect the effect of liner type on the bovine teat are very subjective and because the tested sensor-based methods are very complex to use or have shown limited usability, the aim of this study was to determine the effectiveness of a pressure-indicating film in detecting the effect of liner type on the directly measuring teat load caused by a collapsing liner.

2. Materials and Methods

2.1. Experimental Setup

The experiment was carried out in the laboratory milking parlor of the Leibniz-Institute for Agricultural Engineering and Bioeconomy e.V. (ATB). A conventional milking cluster (GEA Group AG, Düsseldorf, Germany) was used, and the machine vacuum was adjusted to 40 kPa. Alternate pulsation was used at a rate of 60 $\min^{-1}$ and a 60:40 pulsation ratio.

2.2. Artificial Teat

An artificial teat made of silicone was used to investigate the influence of liner type on the teat load caused by a collapsing liner. The teat had a length and a mean diameter of 56 mm and 21 mm, respectively, and it was hollow with a teat wall thickness of 4.5 mm. According to the manufacturer, the silicone rubber had a Shore A hardness of 25, a density of 1.16 $g \cdot cm^{-3}$ at a temperature of 23 °C, a tensile strength of 5.00 $N \cdot mm^{-2}$, an ultimate elongation of 350%, a tear resistance of more than 20 $N \cdot mm^{-1}$, and a linear shrinkage of 0.5%.

2.3. Teat Cup Liners

The teat load on the artificial teat caused by liner collapse was measured for six different liners: a round silicone liner (SilRou), a round rubber liner with head ventilation (RubRouHV), a triangular rubber liner (RubTri), a concave rubber liner (RubCon), a round rubber liner (RubRou), and a square rubber liner (RubSqu). Table 1 shows the technical specifications of the tested liners.

2.4. Pressure-Indicating Film

The Prescale pressure-indicating films by Fujifilm (KAGER Industrieprodukte GmbH, Dietzenbach, Germany) are used to measure pressure, pressure distribution, and pressure balance and are available in mono- and two-sheet types. The two-sheet film consists of a color-forming layer and a color-developing layer, and when pressure is applied to the film, the microcapsules are broken so that the color-forming material reacts with the color-developing material. As a result, red patches appear on the film, and the density of the red color indicates several levels of pressure between 0.05 MPa and 50 MPa. Following the measuring procedure, the C-films can be visualized with a scanner (Epson Perfection V37/V370 Photo, KAGER Industrieprodukte GmbH) and analyzed with the FPD-8010E software by Fujifilm (KAGER Industrieprodukte GmbH). This software analyze six parameters: the proportion within the pressure-detection range of the film (effective rate, ER, in %), the surface area over which the color was generated (pressed area, PA, in mm^2), the mean pressure on the area where the color was generated (average pressure, AP, in MPa), the maximum pressure on the area where the color was generated (maximum pressure, MP, in MPa), the product of the pressurization surface area and the average pressure (load, L, in N), and the measured area (MA, in mm^2).

Table 1. Overview of the tested teat cup liners and their different characteristics.

Liner	1	2	3	4	5	6
Abbreviation	SilRou	RubRouHV	RubTri	RubCon	RubRou	RubSqu
Material	silicone	rubber	rubber	rubber	rubber	rubber
Mouthpiece bore diameter (mm)	23	23	23	20	23	23
Barrel shape	round ●	round ●	triangular Δ	concave Δ	round ●	square □
Barrel diameter at 75 mm (mm)	25	23	-	-	24	-
Side edge length (a) at 75 mm (mm)	-	-	30	30	-	25
Inscribed circle [1] at 75 mm (mm)	-	-	8.7	8.7	-	7.2
Circumradius [2] at 75 mm (mm)	-	-	17.3	17.3	-	14.4
Liner length (mm)	169	156	150	149	159	151
Touchpoint (kPa)	18.4	15.1	-	-	12.9	-
Wall thickness (mm)	2.0	3.0	2.0	2.0	2.0	2.0
Head ventilation	no	yes	yes	no	no	no

[1] Inscribed circle = $\sqrt{3}/6 \times$ a; [2] Circumradius = $\sqrt{3}/3 \times$ a.

2.5. Data Collection

The Extreme Low film (Prescale by Fujifilm; KAGER Industrieprodukte GmbH, Dietzenbach, Germany) was used to determine the influence of different liners on the measured teat load due to liner collapse. The pressure-indicating film was cut into pieces (15 mm × 55 mm), all of which were attached to the teat with tape (Figure 1).

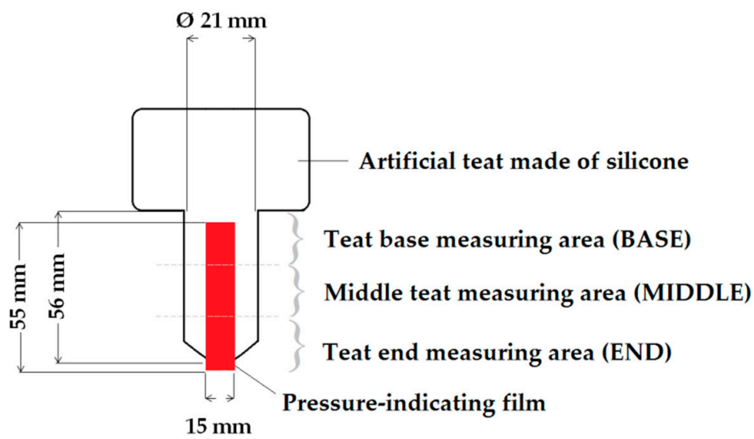

Figure 1. Schematic of the artificial teat with the pressure-indicating film and the three measuring areas.

Due to the small size of the sensor, the teat-sensor-combination was rotated five times in intervals of 30° to record the teat load at each position (Figure 2), and six repetitions were performed for each position. The artificial teat was inserted in the teat cup, and the liner was opened and closed for 30 s. After each session, the artificial teat was turned 30°, and the next measurement was recorded. Thus, the pressure-indicating film measured the pressure at each point of the liner surface at and between the chosen positions.

After measuring, the films were analyzed with the FDP-8010E software by Fujifilm (Prescale by Fujifilm; KAGER Industrieprodukte GmbH, Dietzenbach, Germany). The load, which is the product of the pressurized surface area and the average pressure (L in N), and the maximum pressure in the area over which color was generated (MP in MPa) were used to analyze the influence of the different liners. L and MP were calculated for the film at the three measuring areas (Figure 1). Therefore, the scanned film was divided into the teat base area (BASE), the middle teat area (MIDDLE), and the teat end area (END).

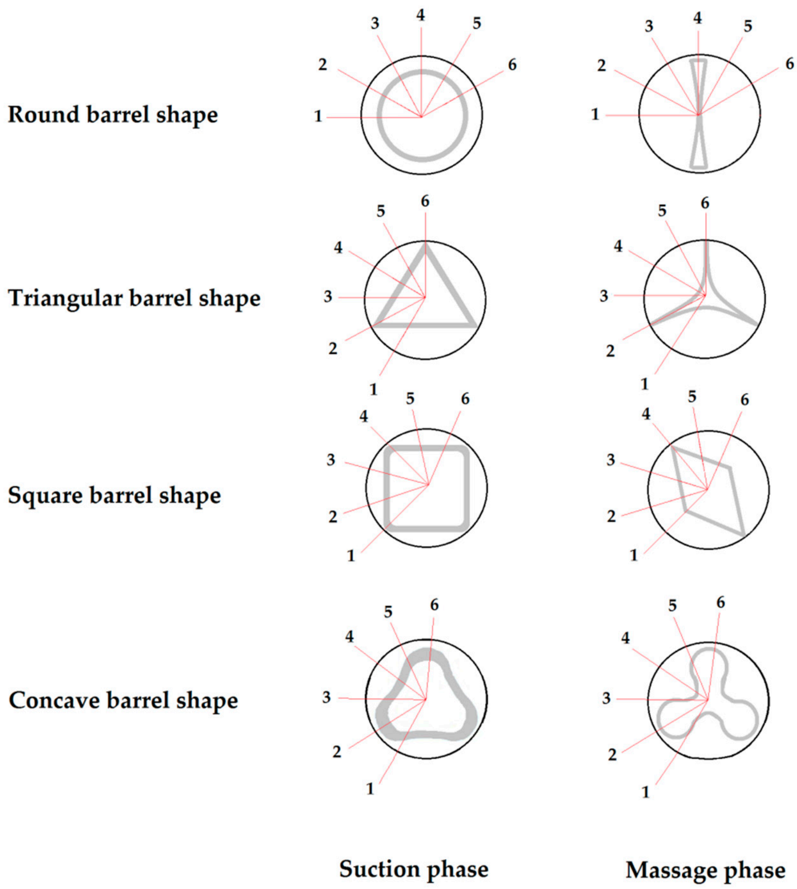

Figure 2. The measurement positions in 30° intervals on the teat cup of the artificial teat for each barrel shape during the suction and massage phases of the milking process.

2.6. Statistical Analysis

Data were analyzed using the SAS 9.4 software package (SAS Institute Inc., Cary, NC, USA), and analysis of variance (ANOVA) was used to estimate the differences in L among the liners and the positions of the artificial teat in the teat cup within a liner for the whole measuring area using the MIXED procedure. The null hypothesis for L was that there were no differences in the tested trait between the liners and the positions within a liner. The following model was used to calculate the influence of the different liner types on L:

$$y_{ijl} = \mu + L_i + P_j + (LP)_{ij} + \varepsilon_{ijl} \quad (1)$$

where y_{ijl} is the observed value of the i-th liner (i = 1, ... ,6) and the j-th position of the artificial teat in the teat cup (j = 1, ... ,6) and the l-th repetition (l = 1, ... ,6); μ is the overall mean; L_i is the fixed effect of the liner type; P_j is the fixed effect of the position in the teat cup; $(LP)_{ij}$ is the interaction between the liner and the position; and ε_{ijl} is the residual.

ANOVA was also used to estimate the differences in L among the liners, the position of the artificial teat in the teat cup, and the three measuring areas using the MIXED procedure, and the null hypothesis for L was that there were no differences among the liners, the positions, and the measuring areas of the tested trait. The following model was used to calculate the influence of the different liner types on L:

$$y_{ijkl} = \mu + L_i + P_j + A_k + (LP)_{ij} + (LA)_{ik} + (PA)_{jk} + (LPA)_{ijk} + \varepsilon_{ijkl} \quad (2)$$

where y_{ijkl} is the observed value of the i-th liner (i = 1, . . . ,6), the j-th position of the artificial teat in the teat cup (j = 1, . . . ,6), the k-th measuring area (k = BASE, MIDDLE, END), and the l-th repetition (l = 1, . . . ,6); μ is the overall mean; L_i is the fixed effect of the liner type; P_j is the fixed effect of the position in the teat cup; A_k is the fixed effect of the measuring area; $(LP)_{ij}$ is the interaction between the liner and the teat position; $(PA)_{jk}$ is the interaction between the position and the measuring area; $(LPA)_{ijk}$ is the interaction between the liner, the position and the measuring area; and ε_{ijkl} is the residual.

The GLIMMIX procedure was used to examine the differences in MP between the liners and the positions of the artificial teat in the teat cup within a liner for the whole measuring area, and the null hypothesis for MP was that there were no differences between the liners and the positions within a liner. A binomial distribution was assumed for MP, and the following model was used:

$$P\left(y_{ijl}\right) = \frac{e^{\eta}}{1+e^{\eta}} \quad (3)$$

The linear predictor η is calculated as follows:

$$\eta_{ijl} = \mu + L_i + P_j + \varepsilon_{ijl} \quad (4)$$

where μ is the overall mean; L_i is the fixed effect of the i-th liner type (i = 1, . . . ,6); P_j is the fixed effect of the j-th position of the artificial teat in the teat cup (j = 1, . . . ,6); and ε_{ijl} is the residual.

The GLIMMIX procedure was also used to examine the differences in MP between the liners, the position of the artificial teat in the teat cup, and the three measuring areas, and the null hypothesis for MP was that there were no differences between the liners, the positions, and the measuring areas. A binomial distribution was assumed for MP, and the following model was used:

$$P\left(y_{ijkl}\right) = \frac{e^{\eta}}{1+e^{\eta}} \quad (5)$$

The linear predictor η is calculated as follows:

$$\eta_{ijkl} = \mu + L_i + P_j + A_k + \varepsilon_{ijkl} \quad (6)$$

where μ is the overall mean; L_i is the fixed effect of the i-th liner type (i = 1, . . . ,6); P_j is the fixed effect of the j-th position of the artificial teat in the teat cup (j = 1, . . . ,6); A_k is the fixed effect of the k-th measuring area (k = BASE, MIDDLE, END); and ε_{ijkl} is the residual.

All tests were carried out at a significance level of 0.05.

3. Results

3.1. Load

3.1.1. Differences between Positions within a Liner for the Whole Measuring Area and between the Measuring Areas within a Liner and Position

In a first step, the differences between the positions within a liner for the whole measuring area were determined. The results of the analysis of variance showed a significant influence of the liner ($p < 0.0001$), the position of the artificial teat in the teat cup ($p = 0.0428$), and the interaction between the liner and the position within a liner ($p < 0.0001$) on L.

For SilRou, L was at least 20.83 N higher at the position where the liner pressed the teat (Position 1) compared to the other positions, and with RubTri, L was 21.17 N higher at the position in the corner of the liner (Position 6) compared to where the liner pressed the teat (Position 4). Where the liner pressed the teat (Position 1), L was at least 21.67 N lower compared to the other positions (Position 2, 3, 5, 6) in RubRou, and for RubSqu, L was at least 22.33 N lower where the liner pressed the teat (Position 1) compared to the other positions. No differences were found between the positions with RubRouHV and RubCon.The standard error for all estimated means was 7.27 N.

In a second step, the measuring areas within a liner and a position were compared. Figure 3 shows the differences in L between the tested liners depending on the position of the artificial teat in the teat cup and the measuring area.

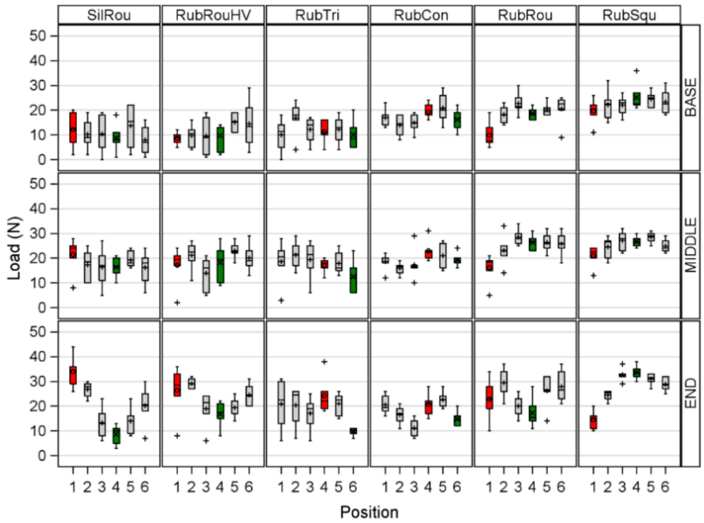

Figure 3. The differences in the measured Load between a round silicone liner (SilRou), a round rubber liner with head ventilation (RubRouHV), a triangular rubber liner (RubTri), a concave rubber liner (RubCon), a round rubber liner (RubRou), and a square rubber liner (RubSqu) depending on the position of the artificial teat in the teat cup (red and green boxes indicate the position where the liner compressed the teat and the position where it bended in the edges, respectively) and the measuring area with BASE = the teat base measuring area, MIDDLE = the middle teat measuring area, and END = the teat end measuring area.

Table 2. The significant differences in L (measured load) and 95%-confidence intervals (CI) between the measuring areas (BASE = teat base measuring area, MIDDLE = teat middle measuring area, END = teat end measuring area) for each liner and position of the artificial teat in the teat cup with a standard error of 3.10 N.

Liner	Position	Compared Measuring Areas	Difference in L (N)	CI	
				Lower	Upper
1	1	BASE-MIDDLE	−9.33	−18.50	−0.17
1	1	BASE-END	−21.83	−33.97	−9.70
1	1	MIDDLE-END	−12.50	−24.64	−0.36
1	2	BASE-END	−16.67	−25.83	−7.50
1	2	MIDDLE-END	−9.50	−18.67	−0.33
1	6	BASE-END	−12.33	−21.50	−3.17
2	1	BASE-END	−17.67	−26.90	−8.43
2	2	BASE-MIDDLE	−11.50	−20.74	−2.26
2	2	BASE-END	−19.50	−28.74	−10.26
2	3	BASE-END	−9.50	−18.74	−0.26
2	6	BASE-END	−10.00	−19.24	−0.76
3	1	BASE-END	−10.83	−20.03	−1.64
3	4	BASE-END	−12.83	−22.03	−3.64
5	1	BASE-END	−13.00	−22.15	−3.85
5	2	BASE-END	−11.33	−20.48	−2.18
6	3	BASE-END	−10.67	−19.87	−1.46

The analysis of variance showed a significant influence of the liner ($p < 0.0001$), the position of the teat in the liner ($p = 0.0007$), and the measuring area ($p < 0.0001$) on L. The interactions between the position and the liner ($p < 0.0001$), the liner and the measuring area ($p < 0.0001$), and the position and the measuring area ($p = 0.0012$) as well as the triple interaction between the position, the liner, and the measuring area ($p < 0.0001$) significantly influence L as well. Within all liners, the highest L was measured at the END compared to the BASE and MIDDLE. Table 2 shows the comparisons of the combinations of measuring areas per liner and the position of the artificial teat in the teat cup, all of which differ significantly.

No differences could be found between the measuring areas of RubCon, so it evenly distributed the pressure on the teat.

3.1.2. Differences between the Liners

To determine differences between the tested liners the positions where the liners compressed the teat (COMP) and the position where the liners did not compress the teat (CORN) were compared between the liners. COMP included position 1 of SilRou, RubRouHV, RubRou, and RubSqu, and position 4 of RubTri and RubCon; CORN included the position 4 of SilRou, RubRouHV, RubRou, and RubSqu, and position 6 of RubTri and RubCon. The comparison of COMP at the BASE area showed that the applied L by RubSqu was 11.00 N, 9.67 N, and 9.83 N higher than this of RubRouHV, RubTri and RubRou, respectively. The L values of RubCon were 10.67 N and 9.33 N higher than these of RubRouHV and RubTri, respectively. The L values of SilRou were 9.83 N, 13.33 N, 11.17 N, and 19.50 N higher at the END than these of RubTri, RubCon, RubRou, and RubSqu, respectively. The applied L of RubRouHV was 11.83 N higher than this of RubSqu. No differences between the liners were found at the MIDDLE.

The comparison of CORN at the BASE resulted in a 9.67 N and 16.33 N lower L for SilRou compared to RubRou, and RubSqu, respectively. L of RubRouHV was 9.67 N, 8.83 N, and 15.50 N lower than of RubCon, RubRou, and RubSqu. The comparison of the three angular liners resulted in a 10.67 N higher load of RubSqu compared to RubTri and RubCon. At the MIDDLE L of RubRou and RubSqu was 10.00 N and 10.33 N higher than this of SilRou, respectively. The L values of RubSqu were 25.00 N, 16.83 N, 9.17 N, 9.17 N, and 16.33 N higher at the END compared to SilRou, RubRouHV, RubTri, RubCon, and RubRou, respectively.

The standard error for all estimated means was 3.10 N.

3.2. Maximum Pressure

3.2.1. Differences between the Positions within a Liner for the whole Measuring Area

No significant differences between the tested liners and the position of the artificial teat in the teat cup within a liner in MP could be found.

3.2.2. Differences between Liners, Positions, and Measuring Areas

Figure 4 shows the differences in MP between the tested liners depending on the position of the artificial teat in the teat cup and the measuring area.

The analysis of variance showed a significant influence of the liner ($p < 0.0001$) and the measuring area ($p = 0.0406$) on MP, but no significant effect of the position of the teat in the teat cup on MP could be found. The MP values were higher for RubRou and RubSqu compared to the other tested liners; the MP of RubRou was 0.04–0.05 MPa higher than that of SilRou, RubRouHV, RubTri, and RubCon. RubSqu showed the highest MP values; the applied pressure was 0.05–0.06 MPa higher than that of SilRou, RubRouHV, RubTri, and RubCon. The MP values were 0.02 MPa higher at the END compared to the BASE, but no significant differences in MP could be found among the other measuring areas.

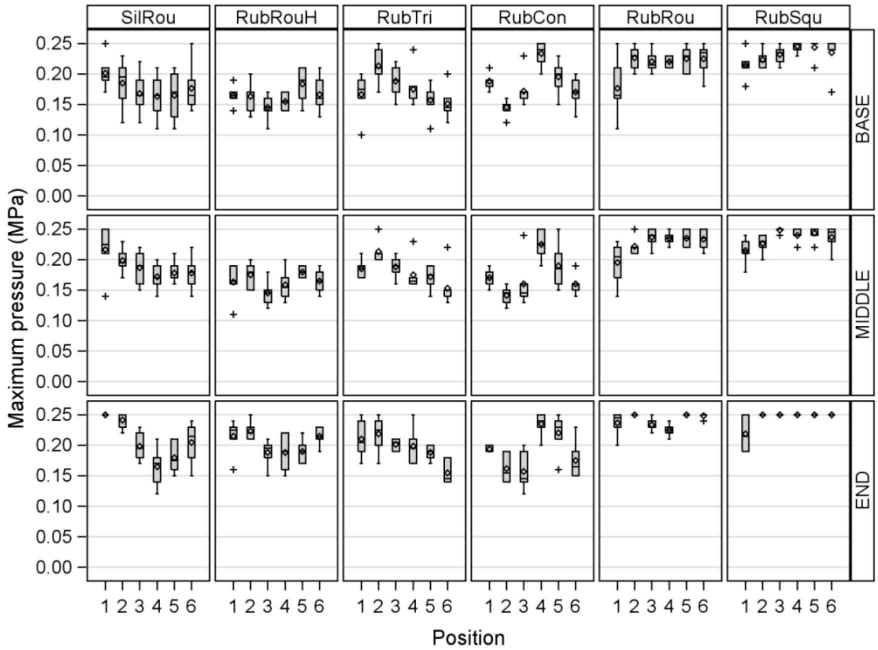

Figure 4. The differences in the measured Maximum pressure between a round silicone liner (SilRou), a round rubber liner with head ventilation (RubRouHV), a triangular rubber liner (RubTri), a concave rubber liner (RubCon), a round rubber liner (RubRou), and a square rubber liner (RubSqu) depending on the position of the artificial teat in the teat cup and the measuring area with BASE = the teat base measuring area, MIDDLE = the middle teat measuring area, and END = the teat end measuring area.

3.3. Conspicuousness Effect of RubCon

The RubCon measurements exhibited a ring at the teat base where more pressure was applied by the liner. This ring was generally apparent within every measurement independent of the position of the artificial teat in the teat cup (Figure 5).

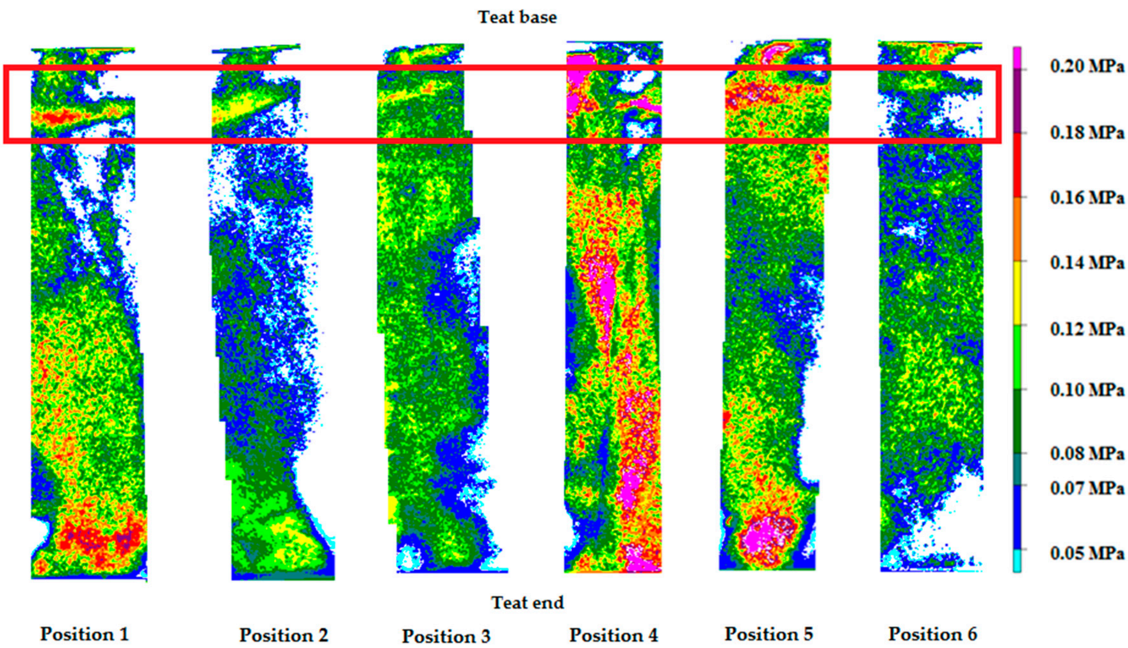

Figure 5. Extreme Low Prescale film scans of each measured position of the artificial teat in the teat cup for the concave liner with the teat base at the top of the figure and the teat end below.

4. Discussion

Different liner types significantly influenced the values of both L and MP, and the different positions of the artificial teat in the teat cup within a liner also affected the teat load caused by a collapsing liner. For SilRou, L was highest at the position where the liner pressed the teat and lowest where the liner bends at the edges (Position 4); these results were confirmed by Tol, Schrader and Aernouts [14] who found similar effects. In contrast, the results for RubRou in the present study did not agree with those of Tol, Schrader and Aernouts [14]. For RubTri, L was higher at the corner than at the position where the liner pressed the teat, which is inconsistent with the results of Tol, Schrader and Aernouts [14] who found only three pressure spots (the three sides where the liner touched the teat) within a triangular liner. However, their artificial teat was 20 mm longer, had a tapered shape, and a 2.5 mm-thinner teat wall compared to the artificial teat used in the present investigation, so this could explain the different results.

Teat load increased from the BASE through the MIDDLE to the END during liner collapse. This result partially agrees with Tol, Schrader and Aernouts [14] who found a similar pressure distribution in round liners. In the present study, the highest teat load was found at the END compared to the other measuring areas. Muthukumarappan et al. [16] confirmed these results, finding that the maximum pressure was applied within 1 or 2 mm of the teat end, and Tol, Schrader and Aernouts [14] also found that the maximum pressure was always applied to the teat end.

The comparison of the different liner types resulted in the highest teat load for SilRou at COMP and END, which disagrees with Tol, Schrader and Aernouts [14]. They found the highest pressure values for a round-square and a triangular liner. Furthermore, the angular liners had a higher teat load at CORN compared with the round liners, which disagrees with the results of Tol, Schrader and Aernouts [14] as well. They found no load in the corners of a triangular liner and observed pressure all around the teat with a square liner. In contrast, Zucali et al. [17] found higher incidences of teat-end hyperkeratosis on farms milking with triangular liners. The use of triangular rubber liners, compared to round rubber liners, did not reduce the traumatization of teats due to milking at different machine vacuum levels [18]. Schukken et al. [19] found a lower frequency of teat ends with crack and teat-end hyperkeratosis in teats milked with square liners. At COMP, the teat load caused by SilRou was higher than that by RubRou, which led to the assumption that a softer material resulted in a higher teat load. Paulrud, Clausen, Andersen and Rasmussen [11] found that milking with a liner made of softer material resulted in colder teats after milking, but Tol, Schrader and Aernouts [14] found similar pressure values for liners made of silicone and rubber. The observations regarding liner material in the present study could be explained by the higher SilRou Touch Point values. The results of Davis, Reinemann and Mein [13] that the compressive load of a liner is proportional to the thickness of the liner wall can neither be confirmed nor refuted because the majority of the liners tested in the present study had a wall thickness of 2.0 mm.

RubCon showed a pressurization ring at the BASE area in all tested positions, which could be explained by the 3 mm-smaller mouthpiece bore diameter. Haeussermann, Britten, Britten, Pahl, Älveby and Hartung [10] compared a concave and a round liner in terms of the effect of each on the degree and roughness of teat-end hyperkeratosis, and they found a lower incidence of rough teat-end hyperkeratosis with RubCon. Unfortunately, they did not investigate the influence of the concave liner on the ring formation at the teat base, so its effects on the teat base remain unknown. On the other hand, Gleeson, O'Callaghan, Meaney and Rath [8] found no significant differences in teat condition between wide-bored and narrow-bored liners.

The measurements with the pressure-indicating film were not influenced by machine vacuum, sensor bending, and shear force. According to Demba et al. [20] neither negative pressure nor sensor bending influenced the measurements by pressure-indicating film. These films do not support shear stress as well [21].

5. Conclusions

It can be concluded that the pressure-indicating film can be used to determine the influence of different liner types on the teat load caused by a collapsing liner because it directly measures the pressure and the load due to liner collapse. Using these measured pressure values, it is possible to objectively compare the effect of the liners on the teat. The pressure applied to the teat depends on the technical characteristics of the teat cup liner, especially the barrel shape. However, there is still a lack of information about the load applied by a collapsing liner, which is necessary to massage the teat, so further studies are needed. Furthermore, it is important to determine the dimensions of the teats in a dairy herd to select the best adapted liner. The artificial teat used in the present investigation was flexible, but in further studies, a teat that is more similar to a natural teat will be used.

Author Contributions: S.D., S.R.-M. and V.P. conceived and designed the experiments; S.D. and V.P. performed the experiments; S.D., V.P. and C.A. analyzed the data; S.D. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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Chapter 5

General Discussion and Conclusion

Introduction

It is general knowledge that machine milking influences the condition of the teat and the teat tissue. The teat load caused by a collapsing liner under several conditions using a new method should be determined according to the research described in the present thesis. The objectives of the present study were to gain further insight into the measured teat load caused by milking and its dependency on several milking conditions. Research has been conducted to examine the usability of measurement of the static pressure distribution and magnitude with the aid of red color density variation to directly measure the teat load caused by a collapsing liner (Chapter 2), the influence of different adjustments of the machine vacuum and pulsation on this measured teat load (Chapter 3), and the effect of the liner type on the measured teat load due to liner collapse (Chapter 4).

Application of the pressure-indicating film in the field of milking

In the present research, the Prescale pressure-indicating film was easy to use and allowed a high sampling rate in a short time. PALETTA ET AL. (1997) found this pressure-indicating film easy to use, reliable, and to provide a high sampling density, and PATTERSON ET AL. (1997) described the film as an accurate and reliable method. The measured pressure values are highly dependent on the material properties (MUTLU ET AL., 2014), as indicated by the significantly different pressure values between the plastic teat and the silicone teat. These differences also indicated that the measured values were only reproducible within the same artificial teat. Changes in the dimensions and the materials of the artificial teat could result in different pressure values. Analyses of the films revealed some white pixels in the teat end area in all investigations. The pressure seemed to be higher or lower at these points than could be measured by the film. Therefore, the measurements of the films were limited to their measuring range. PALETTA ET AL. (1997) also found that the film measurements were limited to their response range. In the present research the maximum pressure per pixel was of interest. If the pressure increase per pixel must be detected, then the films are not usable because they cannot measure this parameter (KUMMER, 2012). According to BARBAGALLO ET AL. (2008), the film is not influenced by moisture, but LIGGINS ET AL. (1995a), PATTERSON ET AL. (1997), and FEI ET AL. (2012) found that the film is moisture and temperature-sensitive. The recommended temperature and relative humidity range from 20°C to 23°C and 35% to

80%, respectively (FEI ET AL., 2012). In the present research, the temperature and humidity conditions were within these ranges, such that the film could be used to detect the teat load caused by liner collapse under laboratory conditions. The film could be sealed to protect it against the influence of moisture and other environmental conditions (LIGGINS ET AL., 1994; BARBAGALLO ET AL., 2008) and to avoid micromotion of the films (LIAU ET AL., 2002), but sealing the film significantly affected the results (LIGGINS ET AL., 1995b). However, the negative effect of sealing the film on the measurement results were determined more than 20 years ago, and therefore this problem may no longer exist. In the present investigations, the films were fixed together with tape to avoid shifting. The film had to be fixed with tape at the artificial teat. These taped areas could be seen in the scanned film because taping of the film resulted in a darkening of the color (PATTERSON ET AL., 1997). Therefore, the taped areas were cut out of the scanned films using the analysis software. As the barrel shape of the used artificial teats was cylindrical, the film had to be bent around the teat, which was possible because the material properties of the films were elastic (LIAU ET AL., 2002). In the present research, bending of the film around the artificial teat had no effect on the measuring results. LIAU ET AL. (2002) also observed perfect bending of the film. In contrast, VILLA ET AL. (2004) determined a significant influence of film bending in response to an applied pressure. The size of the film pieces depends on the problem and aim of the specific investigation. During the present research, the film pieces had sizes of 35 mm x 45 mm or 15 mm x 55 mm to analyze the teat load caused by a collapsing liner and were used as one sample area. This process has been found to be suitable to achieve the aims of the present research. Smaller sample areas of the film or a pixel-by-pixel analysis may be helpful to obtain deeper insight into the teat-liner interface. LIGGINS ET AL. (1995a) used sample areas of 0.5 mm x 0.5 mm or 1.0 mm x 1.0 mm to investigate the pressure caused by artificial joints. During the present research, the insertion of the artificial teat had no influence on the pressure results because the head diameters of the used liners were sufficiently wide. LIAU ET AL. (2001) also failed to detect a sliding effect caused by insertion of the film. However, the insertion of the film between two objects could have an effect on the results. LIAU ET AL. (2001) found an overestimation of the real contact area of the film by 20% to 25% due to insertion of the film. In the present investigations, the pressure applied by a collapsing liner ranged between 0.07 MPa (70 kPa) and 0.64 MPa (640 kPa), depending on the artificial teat, film type, measurement area, vacuum level, pulsator adjustments, and liner type. Pressure values of 18-35 kPa (MUTHUKUMARAPPAN ET

AL., 1994), 20-41 kPa (DAVIS ET AL., 2001), 99-180 kPa (TOL ET AL., 2010), and 20-34 kPa (LEONARDI ET AL., 2015) were found in earlier studies. Thus, the pressure values found in the present investigations were much than those reported in other studies. These results are in agreement with those of HENAK ET AL. (2014) and MUTLU ET AL. (2014), who found that the Prescale pressure-indicating film measures a higher maximum pressure compared with the other methods.

Comparison of teat load determination methods

With visual observation, it is possible to determine the influence of machine milking on the teat condition. Therefore, several scoring systems are available that concern teat color, swelling, ring formation at the teat base, and teat end hyperkeratosis (RASMUSSEN ET AL., 1998; CAPUCO ET AL., 2000; MEIN ET AL., 2001; GLEESON ET AL., 2005; ZUCALI ET AL., 2008; HAEUSSERMANN ET AL., 2016). Thereby, the teat score depends on the evaluating person, the scoring system, the light conditions, and the cleanliness of the teats, and thus is an indirect and subjective teat load determination method. In contrast, measurement of the static pressure distribution and magnitude with the aid of red color density variation is a direct and objective measurement method to determine the teat load due to liner collapse. It can be performed by any person and is not as greatly influenced by environmental conditions as teat scoring. However, although it provides information about the pressure applied to the teat, it gives no information about the effect of this pressure on the teat tissue.

Calculation of the Touch Point (TP), the residual vacuum available for massage, the Liner Compression (LC), the over-pressure (OP), and the true milk : rest ratio are the most commonly used methods to estimate the teat load due to liner collapse. Pressure differences were calculated within all methods (MEIN AND REINEMANN, 2009), which were therefore only indirect estimation methods. According to REINEMANN AND MEIN (2011), LC is the most biologically relevant way to measure the pressure applied to the teats by a liner, but it is not the same as direct pressure measurements with a pressure sensitive film and an artificial teat.

Ultrasonography is a usable tool to determine the influence of milking on teat tissue parameters and changes in teat anatomy in real life (NEIJENHUIS ET AL., 2001; PAULRUD ET AL., 2005). Nevertheless, ultrasonic imaging is not able to supply information about the pressure applied to the teat caused by liner collapse. It is a complex method to use because of the handling and the needed materials (water bath, contact gel). According to PAULRUD ET AL. (2005), infrared thermography is a usable tool to investigate the effect of machine milking on teat temperature and, thus, on the blood flow in teats. With thermography, the short and longer-term tissue reactions to milking can be evaluated, but they provide no information about the pressure applied by a liner. Furthermore, measurements of using an infrared camera can be influenced by light conditions, dirt or moisture on the investigated surface, direct air movement over the investigated surface, and the ambient temperature (JIANG ET AL., 2005; KNÍŽKOVÁ ET AL., 2007).

In earlier studies, several pressure-sensitive sensors were used to determine the compressive load applied to the teat by a teat cup liner. The sensor used by GATES AND SCOTT (1986) had some disadvantages compared with the pressure-indicating film used in the present research. It must be directly connected with a PC, and while the authors describe the sensor as temperature-insensitive, changes in temperature affect the measurement results and their sensitivity. MUTHUKUMARAPPAN ET AL. (1994) tested the usability of thin film sensors to measure this load, but the sensor provided unsatisfactory results. It showed significant measurement errors caused by bending. As shown in Chapter 2, the used pressure-indicating film was not influenced by bending around the artificial teat. ADLEY AND BUTLER (1994), DAVIS ET AL. (2001), and LEONARDI ET AL. (2015) used similar teat sensors that differed slightly in their construction. Basically, all three sensors were composed of a pressure sensor (miniature load cell or force sensors) containing artificial teat. Therefore, the sensors could only be used with this specific artificial teat, while the pressure-indicating film applied in the present research is flexible to use. TOL ET AL. (2010) investigated the teat-liner interface with a flexible pressure-sensitive sensor. This sensor was not influenced by bending around the teat, the data were transduced via Bluetooth, pressure images could be easily translated to Microsoft Excel files, and it was not sensitive to shear stress. Nevertheless, this sensor had one disadvantage: While the pressure-indicating film used in the present research can be cut into pieces with different sizes, the pressure sensor used by TOL ET AL. (2010) was only available in one size. ROŞCA et al. (2017) investigated the influence of the liner type, pulsation rate, and pulsation ratio on the teat-liner contact pressure with the help of a force sensor. With this sensor, it is possible to directly transduce the pressure values to a PC, but the sensor must be connected with the PC while acquiring the measurements. While the whole film area of the pressure-indicating film used in the present investigations is the sensing area, the sensing area of the sensor used by Roşca et al. (2017) has a diameter of only 9 mm, making it impossible to measure the teat load caused by liner collapse over the whole teat barrel (only selective measurements are feasible).

It could be concluded that measurement of the static pressure distribution and magnitude with the aid of red color density variation had some disadvantages, but in comparison to the other applied teat load determination methods, the advantages of the film prevailed. Thus, the hypothesis that the tested method is appropriate to directly measure the teat load caused by a collapsing liner could be confirmed.

Influential factors on teat load due to liner collapse

Adjustments of the machine vacuum affected the teats of dairy cows. During the present research, the measured values for the average pressure, maximum pressure, and load increased as the machine vacuum increased, and thus it can be assumed that an increasing machine vacuum resulted in a higher teat load caused by a collapsing liner. This assumption agrees with the majority of the literature. Hamann and Mein (1988) and Hamann (1988) found that the teat end thickness and tissue stiffness increased with an increasing vacuum level. Higher vacuum levels resulted in an increase in teat thickness by 10-15% (Hamann and Mein, 1990) or by 25% (Spanu et al., 2008) and thicker and shorter teats with smaller diameters and less compressibility immediately after milking (Hamann et al., 1993). Milking with a higher vacuum level resulted in significant changes in teat anatomy (Parilova et al., 2011; Besier and Bruckmaier, 2016). The results of the present research are consistent with those of Ebendorff and Ziesack (1991) and Rose-Meierhöfer et al. (2014), who determined better teat color scores in teats milked with a lower vacuum. The development of teat end hyperkeratosis increased with a high machine vacuum (Ryšánek et al., 2001; Neijenhuis et al., 2005). In contrast, Reinemann et al. (2001) and Gleeson et al. (2003) did not observe a significant influence of the machine vacuum on hyperkeratosis. Similarly, Ambord and Bruckmaier (2010) did not observe changes in teat conditions caused by the machine vacuum. The TP, OP, and LC values also rose with an increasing vacuum level (Mein et al., 2003; Spencer et al., 2007; Bade et al., 2009; Reinemann and Mein, 2011). In the present research, the average pressure, maximum pressure, and load were lowest at a machine vacuum of 30 kPa. Because of this relationship between the milking vacuum and teat load, and because a certain pressure of the liner is needed to massage the teat, the claw vacuum level should not be less than 30 kPa (BESIER AND BRUCKMAIER, 2016).

The pulsation rate and the pulsation ratio also influenced the teat of a cow during milking. In the present research, the average pressure, the maximum pressure, and the load rose with an increase in pulsation rate. Furthermore, HANSEN ET AL. (2006) found less stressed teats with a lower pulsation rate. In contrast, ROȘCA et al. (2017) determined a decreasing maximum contact pressure with an increasing pulsation rate. The values for maximum pressure and load and thus the teat load during liner collapse decreased with shorter c- and d-phases of pulsation. In contrast, ROȘCA et al. (2017) recorded higher contact pressure values for a pulsation ratio of 60:40 compared with a pulsation ratio of 50:50. The results of the present research are in agreement with UPTON ET AL. (2016), who found a significant reduction in the estimated cross-sectional area of the teat canal with shorter d-phase durations. BADE ET AL. (2009) detected less teat end tissue congestion with an increasing b-phase duration. In contrast, BLUEMEL ET AL. (2016) found that an extended c phase indicated gentler milking. The calculated values of OP slightly increased with shortening of the c phase duration (MEIN ET AL., 2003). According to REID AND JOHNSON (2003), the d phase duration should be at least 200 ms. However, an increase of the suction phase resulted in an increase in teat end congestion (GRINDAL, 1988; REINEMANN ET AL., 2008). The results of the present research disagree with GLEESON ET AL. (2004) and FERNEBORG AND SVENNERSTEN-SJAUNJA (2015), who did not observe a negative effect of different pulsation ratios.

In the present research, six liners were compared with respect to their applied pressure to the teat: a round silicone liner (SilRou), a round rubber liner with head ventilation (RubRouHV), a triangular rubber liner (RubTri), a concave rubber liner (RubCon), a round rubber liner (RubRou), and a square rubber liner (RubSqu). In a first step, the positions of the artificial teat within a liner were compared. The results of the tested round liners were contradictory: while SilRou applied the highest pressure at the position where the liner pressed the teat and lowest pressure where the liner bent at the edges, RubRou applied the lowest pressure where it pressed the teat. According to TOL ET AL. (2010), round liners concentrated the load over the two sides where the liner touched the teat end and decreased it to almost zero between these two points, which is consistent with the results obtained for SilRou but not with those for

RubRou. With RubTri the teat load was higher at the corner than at the position where the liner pressed the teat. In contrast, TOL ET AL. (2010) determined the three sides where the liner touched the teat as pressure spots within triangular liners. For RubSqu, the pressure was lowest at the position where the liner pressed the teat. The differences between the results obtained in the present research and these of TOL ET AL. (2010) could be explained by the different artificial teats. In contrast to the present analysis, they used a 20 mm longer, taper shaped teat with a 2.5 mm-thinner teat wall. RubRouHV and RubCon appeared to apply even applied the pressure over the teat because there were no differences between the positions within these liners. In a second step, the differences between three measuring areas were compared within a liner and position. The whole measurement area of the film was divided into the teat base measuring area (BASE), the middle teat measuring area (MIDDLE), and the teat end measuring area (END). During the present research, the teat load due to liner collapse increased from the BASE through the MIDDLE to the END. TOL ET AL. (2010) observed similar pressure distributions for round liners. Independent of the liner type, the highest teat load caused by a collapsing liner was found at the END. This result is consistent with the findings of MUTHUKUMARAPPAN ET AL. (1994), who observed that the maximum pressure was applied within 1 or 2 mm of the teat end and that the pressure decreased gradually over the upper 3 or 4 mm of the teat apex. TOL ET AL. (2010) also found that the highest pressure was always applied to the teat end. In a third step, the liners were compared with each other. Therefore, the positions where the liners compressed the teat and the positions where the liners bent at the edges were compared between the liners. SilRou applied the highest teat load at the position where the liner compressed the teat compared with the other tested liners. This result is in agreement with LEONARDI ET AL. (2015), who found a significant higher OP for round liners compared to triangular liners. In contrast, TOL ET AL. (2010) determined the highest pressure values for a round-square and a triangular liner. According to ZUCALI ET AL. (2009) and HAEUSSERMANN ET AL. (2011), milking with triangular-shaped liners resulted in a lower incidence of teat end hyperkeratosis in comparison to round liners. In contrast, KUNC ET AL. (1999) did not identify a reduced teat load by using triangular liners. Milking with square liners resulted in fewer teat ends with cracks and hyperkeratosis (SCHUKKEN ET AL., 2006). The use of multi-sided concave liners resulted in a lower frequency of rough hyperkeratosis compared with a conventional round liner (HAEUSSERMANN ET AL., 2016). The teat load caused by SilRou was higher than that caused by RubRou at the position where the liner compressed the teat. Therefore, it could be assumed that milking with liners made of silicone resulted in higher teat loads. This finding is inconsistent with the results of MEIN AND REINEMANN (2009), who observed less congestion in teats milked with silicone liners. PAULRUD ET AL. (2005) found colder teats after milking with a liner of softer material. ROȘCA et al. (2017) found much lower contact pressure values with a silicone liner in comparison to a rubber liner. In contrast, TOL ET AL. (2010) did not detect differences in the pressure values between liners made of rubber and those made of silicone. The higher TP values of SilRou could be an explanation for the higher teat load due to SilRou. At the position where the liner bent at the edges, the angular liners applied more pressure to the teats than the round liners. This result is in contrast to the findings of TOL ET AL. (2010), who showed no load at the corners of triangular liners and observed an even pressure distribution around the whole teat with square liners.

In summary, hypothesis 2 and hypothesis 3 could be confirmed with the present research because the teat load caused by a collapsing liner was significantly affected by adjustment of the milking settings and liner type. Therefore, the milking settings and liners should complement each other and should be very well adapted to the dairy herd.

Conclusion and further research

Measurement of the static pressure distribution and magnitude with the aid of red color density variation is a usable, direct, and objective method to investigate the teat-liner interface and to determine the teat load on an artificial teat caused by a collapsing liner under comparative conditions. The advantages of using this method prevailed compared with other teat load determination methods. Based on the results of the present research, a pressure-indicating film with a measuring range of 0.05-0.6 MPa would be usable to optimize the results. Nevertheless, the reproducibility of the data must be considered critically. The artificial teats used herein are unique, and it is not possible to recreate them. Measurement of the teat load using the same method but different artificial teats could change the results. Thus, the collected pressure values were only reproducible for the used artificial teats. The use of a standardized artificial teat could be helpful to improve the reproducibility of the measurements. Further studies are also needed to gain further insight regarding the-teat liner interface. These studies could have two main focuses. On the one hand, the data could be analyzed in different ways. Smaller sample areas of the film or a pixel-by-pixel analysis could be used. On the other hand, it is important to measure the pressure caused by a collapsing liner on an artificial teat that is more similar to a natural teat. In all investigations, artificial teats made of plastic or silicone were used. An isolated perfused udder may be usable to achieve this aim. In this case, it is important to clarify the attachment of the film on the teats. Whether the film is appropriate to measure the teat load in combination with water and milk flow should also be assessed. Earlier results regarding the influence of moisture on the measurement results of the pressure-indicating film have been contradictory, and therefore the effect of moisture on the measuring results should be addressed. In earlier studies, sealing the film protected it against water, but in some of these studies it negatively affected the measurement results. Therefore, the influence of sealing the film on the measured pressure values should be investigated as well.

The teat load due to liner collapse depends on the machine vacuum level, pulsation adjustments, and liner type. Therefore, the machine vacuum and pulsation must be optimally adjusted to determine the balance between massaging the teat and preventing damage to the teat by the liner. In the literature, it is advised that the machine vacuum and the claw vacuum should not be lower than 30 kPa and should not exceed 42 kPa. These statements can neither be confirmed nor rejected based on the results of the present investigation. The influence of the investigated machine vacuum levels does not allow a clear conclusion about the amount of vacuum for gentle milking. Therefore, the influence of the teat end vacuum on the teat load caused by a collapsing liner should be investigated. According to the literature, the pulsation rate should be adjusted to approximately 55-60 min^{-1}, and the pulsation ratio should be well balanced between the suction and the massage phase. The optimal durations of the pulse cycle phases regarding the teat load due to liner collapse must be analyzed in future investigations. The teat load caused by liner collapse depends primarily on the shape of the liner barrel. It is important to determine the dimensions of the teats in a dairy herd to select the best-adapted liner. Due to price differences between the different liners, both costs and benefits of the liners should be taken into account. Further research should compare different milking systems in terms of their influence on the teat load, as well as the effect of liner.

Summary

Public attention has been increasingly focused on the welfare of dairy cows, requiring continuous improvements in their housing conditions and steady development of the milking technique. Although, the milking technique has been continuously developed to achieve a gentler milking process, there remains a lack of information about the teat load caused by a collapsing liner. Therefore, the aims of the present thesis were ,first, to test, whether measurement of the static pressure distribution and magnitude with the aid of red color density variation is appropriate to directly measure the teat load due to liner collapse and, second, to determine the effects of the machine vacuum level, pulsation rate, pulsation ratio, and liner type on this teat load using this method.

As a first step, the usability of measurement of the static pressure distribution and magnitude with the aid of red color density variation to measure directly the teat load caused by a collapsing liner was tested. Therefore, two film types of a pressure-indicating film with different pressure ranges (Film 1: 0.2-0.6 MPa, Film 2: 0.05-0.2 MPa) and two artificial teats (plastic, silicone) were used. Both Film 1 and Film 2 were able to measure the teat load on the plastic teat as well as on the silicone teat. Based on these results, Film 2 was more suitable than Film 1 as a tool to measure the teat load on both artificial teats because more color developed on the film. Therefore, subsequent investigations were carried out with Film 2. With this investigation it was also determined that neither bending of the film nor negative pressure affected the measurement results.

To assess the influence of different milking settings on the teat load due to liner collapse, Film 2 as well as a hollow artificial teat made of silicone were used. Different machine vacuum levels (30 kPa, 40 kPa, 50 kPa), different pulsation rates (40 cycles min^{-1}, 60 cycles min^{-1}, 80 cycles min^{-1}), and different pulsation ratios (60:40, 65:35, 70:30) were chosen as influencing factors. All three factors significantly influenced the teat load caused by a collapsing liner; the higher the machine vacuum, the pulsation rate, and the pulsation ratio, the higher was this teat load. The teat load was higher at the end of the artificial teat compared with the whole teat.

The same film type and artificial teat were used to determine the effect of the liner type on the teat load due to liner collapse. Six different liners, which differed in the shape of their barrel, material, and technical characteristics, were compared regarding their applied teat load. The teat load caused by liner collapse depends on technical characteristics, especially the shape of the barrel. For all tested liners, the highest teat load was found at the teat end.

The overall conclusions of this thesis are that measurement of the static pressure distribution and magnitude with the aid of red color density variation is a usable, direct, and objective method to determine the teat-liner interface and that different milking conditions affect this interface. Therefore, the milking settings and liners should complement each other and should be very well adapted to the dairy herd. In the long term, the results of the present thesis could help to improve milking with respect to teat damage and udder health.

Zusammenfassung

Die Aufmerksamkeit der Öffentlichkeit richtet sich mehr und mehr auf das Wohlbefinden von Milchkühen. Um dieses zu verbessern, sind eine stetige Verbesserung der Haltungsbedingungen der Kühe sowie eine kontinuierliche Weiterentwicklung der Melktechnik nötig. Obwohl die Melktechnik hinsichtlich der euterschonenden Gestaltung des Melkvorganges in den letzten Jahrzehnten stetig weiterentwickelt wurde, ist die Beziehung zwischen Zitze und Zitzengummi beim Melken nicht ausreichend geklärt. Daher war es das Ziel dieser Dissertation zu untersuchen, ob sich die Messung statischer Drücke in unterschiedlichen Größenordnungen mit Hilfe von roter Farbdichtevariation zur direkten Messung des Druckes zwischen Zitze und Zitzengummi beim Melken eignet. Der Einfluss verschiedener Vakuumlevel, Pulsationsraten, Pulsphasenverhältnisse und Zitzengummis auf den Druck zwischen Zitze und Zitzengummi wurde ebenfalls mit Hilfe dieser Methode analysiert.

Im ersten Schritt wurde die Eignung der Messung statischer Drücke in unterschiedlichen Größenordnungen mit Hilfe von roter Farbdichtevariation zur direkten Messung des Druckes zwischen Zitze und Zitzengummi beim Melken untersucht. Dafür wurden zwei Folienarten einer Druckmessfolie mit unterschiedlichen Druckbereichen (Film 1: 0.2-0.6 MPa, Film 2: 0.05-0.2 MPa) und zwei Zitzenmodelle (Plastik, Silikon) verwendet. Mit beiden Folienarten war es möglich den Druck direkt zwischen dem Zitzengummi und beiden Zitzenmodellen zu messen. Basierend auf den Ergebnissen war Film 2 besser geeignet als Film 1, da sich auf diesem Film mehr Farbe entwickelt hat. Deshalb wurden die folgenden Untersuchungen mit Film 2 durchgeführt. Mit dieser Untersuchung wurde außerdem festgestellt, dass weder das Biegen der Folie noch Unterdruck einen Einfluss auf die Messergebnisse haben.

Um den Einfluss verschiedener Melkeinstellungen auf den Druck zwischen Zitze und Zitzengummi zu analysieren, wurden Film 2 sowie ein hohles Zitzenmodell aus Silikon genutzt. Als Einflussfaktoren wurden unterschiedliche Einstellungen des Anlagenvakuums (30 kPa, 40 kPa, 50 kPa), verschiedene Pulsationsraten (40 Zyklen min^{-1}, 60 Zyklen min^{-1}, 80 Zyklen min^{-1}) und unterschiedliche Pulsphasenverhältnisse (60:40, 65:35, 70:30) ausgewählt. Für alle drei Faktoren konnte ein signifikanter Einfluss auf den Druck zwischen Zitze und Zitzengummi nachgewiesen werden. Dieser stieg mit zunehmendem

Anlagenvakuum, zunehmender Pulsationsrate und zunehmendem Pulsphasenverhältnis an. Dabei war der Druck am Zitzenende höher verglichen mit der gesamten Zitze.

Dieselbe Folienart und das selbe Zitzenmodell wurden genutzt, um den Effekt verschiedener Zitzengummis auf den Druck zwischen Zitze und Zitzengummi beim Melken zu analysieren. Dafür wurden sechs Zitzengummis, welche sich in ihrer Form, ihrem Material und ihren technischen Eigenschaften voneinander unterschieden, miteinander verglichen. Es stellte sich heraus, dass vor allem die Form eines Zitzengummis den Druck zwischen Zitze und Zitzengummi beeinflusst. Bei allen untersuchten Zitzengummis war der Druck an der Zitzenspitze am höchsten.

Abschließend lässt sich schlussfolgern, dass die Messung statischer Drücke in unterschiedlichen Größenordnungen mit Hilfe von roter Farbdichtevariation eine geeignete, direkte und objektive Methode zur Erfassung des Druckes zwischen Zitze und Zitzengummi beim Melken ist. Außerdem haben verschiedene Melkeinstellungen und Zitzengummis einen unterschiedlichen Einfluss auf den entstehenden Druck. Daher sollten die Melkeinstellungen und Zitzengummis aufeinander abgestimmt und an die Herde angepasst werden. Auf lange Sicht können die Ergebnisse dieser Dissertation dazu beitragen, den Melkvorgang hinsichtlich Zitzenschädigungen und Eutergesundheit zu verbessern.

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Hiermit erkläre ich, die Dissertation selbstständig und nur unter Verwendung der angegebenen Hilfen und Hilfsmittel angefertigt zu haben. Ich habe mich anderwärts nicht um einen Doktorgrad beworben und besitze keinen entsprechenden Doktorgrad. Ich erkläre, dass ich die Dissertation oder Teile davon nicht bereits bei einer anderen wissenschaftlichen Einrichtung eingereicht habe und dass sie dort weder angenommen noch abgelehnt wurde. Ich erkläre die Kenntnisnahme der dem Verfahren zugrunde liegenden Promotionsordnung der Landwirtschaftlich-Gärtnerischen Fakultät der Humboldt-Universität zu Berlin vom 31. März 2014. Weiterhin erkläre ich, dass keine Zusammenarbeit mit gewerblichen Promotionsbearbeiterinnen/Promotionsberatern stattgefunden hat und dass die Grundsätze der Humboldt-Universität zu Berlin zur Sicherung guter wissenschaftlicher Praxis eingehalten wurden.

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